THE UNIVERSITY OF ALBERTA

A MATHEMATICAL MODEL FOR A TWO-STAGE CONCENTRATING EVAPORATOR

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ABSTRACT

A two-stage evaporator has been built and brought into fully-controlled operation utilizing a control scheme which has some merit over the more common control schemes reported in the literature. In the control configuration used here, steam rate is employed as the manipulated variable in controlling product composition. The product rate from each effect is the manipulated variable in controlling the respective levels. The conventional method of evaporator control utilizes product rate to control product composition and the feed rate to each effect to control the levels.

An advantage of the control scheme used in this work, over the conventional control scheme, results from not having committed feed rate as a manipulated variable. Thus feed rate may be determined by throughput requirements of other components of the system. For the conventional control scheme, the evaporator throughput can only be altered by changing the steam rate. However, the product composition is very sensitive to steam rate and thus to use steam rate for automatic control of throughput would result in considerable interaction between the steam flow and the product composition control loops.

It is shown, in this work, that besides providing this advantage the control scheme used here should result in better control, since the response of product composition to steam changes is faster than the response to product rate

changes. This is established for this system only but should be true for the majority of evaporator installations.

A mathematical model to describe the transient behavior of this evaporator has been developed. The technique used in the derivation of this model was to consider the evaporator as being made up of several interacting sections or modules. Each module was then analyzed separately as to its dynamic significance. If the differential equations which described a particular module exhibited a relatively rapid response they were replaced with algebraic steady state equations. In this way the model was simplified to where its solution was possible in reasonable computer time.

The model was solved on an IBM 7040 computer using a fourth-order Runge-Kutta-Gill integration routine. Comparisons between the predicted transient response and experimental data were made for 3 open-loop and 3 closed-loop experiments employing a variety of input disturbances. The predicted and actual transient responses showed good agreement and since the predicted response is obtained in approximately 0.5% of real time it is felt the model developed here is a reasonable one. A linear version of the model was also developed which produced results that agreed fairly well with those of the non-linear model.

TO STUBIT

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I. INTRODUCTION

In general evaporation may be defined as the removal of solvent from a solution in which the solute is non-volatile at the operating conditions. While this definition may be applied to several processes and may involve a variety of solutions, in the vast majority of cases that a chemical engineer might encounter, the solvent is water, the heat required to affect the evaporation is supplied by condensing steam and the heat from the steam is transmitted to the solution indirectly through metallic surfaces(24).

As such, the evaporator first came into use about 1800 when steam-heated open pans of various designs were in use in the sugar industry. The first real advance in evaporator design was the invention of the vacuum pan by Howard in 1812. The first multiple-effect evaporator was made for the sugar industry in 1834(2). Since that time there have of course been many improvements in evaporator design and many different types developed, but it is interesting to note that the current "workhorse" of steam-heated evaporators, the long-tube-vertical evaporator was invented by Kestner in 1899(24).

Of course it should not be inferred from the above that there has been no improvement in evaporator design since the turn of the century. Our improved knowledge of heat transfer mechanisms, boiling, scaling, crystallization, equipment fabrication etc. has led to considerably more efficient

evaporator design and operation. But until recent times, automatic control is one aspect of evaporator operation which had not received much attention.

In order to study the control of any process, device or system a knowledge of its transient behavior is required. The most useful description of the transient behavior is provided by a mathematical analog of the system usually referred to as the model. Obtaining a model for complex processes such as evaporation can be a formidable task since the normal material and enthalpy balances of the steady state now become non-linear differential equations which can be extremely complicated if the process is modelled exactly. For such a case, it may be that any economies that might be gained through a knowledge of this transient behavior would be lost due to the cost of solving the model. Consequently, during the modelling of a complex process it is necessary to strike a compromise between retention of complexities for accuracy and simplification for expediency. Unfortunately, as pointed out by T.J. Williams(25), at present there is no generally accepted basis for simplification of a model. Also there is no simple procedure for determining the dynamic significance of the individual differential equations of the model. The procedure adopted in this work was to examine the response rate of proposed differential equations and to assume steady state for those equations having a rapid response.

While this procedure is not generally applicable to all sets of differential equations it can be used if the nature of the process being described is kept in mind. The results achieved in this work would seem to support this conclusion, at least for this evaporator.

The evaporator used in this study consisted of two effects, the first being of the calandria or short-tube-vertical type and the second being of the forced-circulation type. This configuration was chosen, firstly because the evaporator is to become an undergraduate unit operations experiment at the completion of this work. Having two different effects should enhance the educational value of the equipment. Secondly, it was hoped that this variety would make the model developed in this work more versatile. Finally, a forced circulation effect is frequently employed where drastic increases in viscosity arise from concentration of the solution. The solution selected for concentration in the evaporator was sugar-water.

When this project was initiated it was decided that the objectives would be;

1) To build a fully controlled two-stage evaporator.
2) To develop a model to describe the transient behavior.
3) To compare the actual and theoretical transient behaviors.

It is hoped that this study will contribute to the knowledge of evaporator control system design and indeed to the general knowledge of process dynamics.

II. INTRODUCTORY THEORY

Examination of the definition of an evaporator given in Chapter I shows that a single-effect evaporator is actually just a special type of heat exchanger. Thus, evaporator theory is merely a branch of heat transfer theory. Consider, however, the problems that arise in the prediction of heat-transfer coefficients for this type of heat exchanger.

If the fluid flowing through a vertical-tube evaporator is below its saturation temperature its heat transfer coefficient can be predicted with reasonable accuracy using the standard equations describing heat transfer in circular tubes. However, if boiling occurs as the fluid rises in the tubes, the heat transfer coefficient is more difficult to predict since the coefficient increases due to the additional turbulence created by the growing bubbles. Also, as vapor is formed the velocity increases, as dictated by continuity considerations, to compensate for the decreased bulk density. This effect is autocatalytic and results in marked increases in the heat-transfer coefficients at successfully higher positions. For the outside of the tube there is the complication of decreasing heat-transfer coefficient, from top to bottom, due to increasing film thickness.

Consider also the problem of determining the temperture drop between fluid and tube wall. As the solution moves up the tube from the bottom, its temperature increases from

heating and its pressure decreases due to fluid friction. When boiling starts there are rapid changes in pressure resulting from the changing hydrostatic head and increasing velocity. These effects create considerable changes in the temperature difference along the tube(7).

Because of the above-mentioned problems the usual practise in evaporator design is to use an overall heat-transfer coefficient predicted from the performance of evaporators operating under similar conditions(3). This overall coefficient is usually based upon a temperature difference defined as the temperature of the saturated steam minus the saturation temperature of the concentrated solution at the pressure in the vapor space of the evaporator. Fortunately there are available in the literature correlations of overall heat transfer coefficients versus temperature drop and boiling temperature for the more common evaporator types.

Considering a heat exchanger as a resistance to the flow of heat then a multiple-effect evaporator can be viewed as a number of resistances in series. The overall driving force for the heat is the temperature difference between the steam in the first effect and the saturation temperature of the solution in the last. If the overall resistance is doubled, say by doubling the number of effects, then the flow of heat will be halved. Thus, the steam consumption, and thereby the evaporation from each effect, will also be halved. However,

since the number of effects is doubled, the net evaporation will be the same(24).

Since the major operating expenses of an evaporator are the steam and cooling water costs, it is seen that the design of a multiple-effect evaporator involves a compromise between capital and operating costs. This is, of course, an over-simplified statement of the solution to evaporator design problems since such things as boiling-point rise, crystallization, scaling, corrosion and heat sensitive solutes may strongly influence the design.

Suffice it to say here that the design of an evaporator installation can be a very difficult task, but since evaporation is a standard unit operation and design techniques have been set out in several publications (2,3,4,15,22), further discussion here would merely be redundant.

Although the subject matter of this thesis also falls within the realm of process control theory, the understanding of the thesis is not contingent upon a knowledge of process control theory and for this reason only pertinent concepts will be introduced here. One aspect of process control theory, namely frequency response, is mentioned several times in the forthcoming chapters and thus warrants some preliminary explanation.

If the input to a stable linear system is forced to oscillate sinusoidally at some fixed frequency ω, then after a

certain period of time the output will also oscillate sinusoidally at that frequency but not necessarily in phase or with the same amplitude as the input. In general, for a specific system, a unique relationship exists between the ratio of the output to input amplitude and the output to input phase difference and the frequency of the forcing sine wave. The spectrum of amplitude ratios and phase angles for various frequencies is referred to as frequency data later in this thesis.

If the transfer function relating input to output of the system in Laplace transform notation is

$$\frac{Y(s)}{X(s)} = G(s)$$

where

$X(s)$ = transform of the system input

$Y(s)$ = transform of the system output

$G(s)$ = transform of the transfer function

then it can be shown(5) that if $i\omega$ is substituted for s in $G(s)$, the amplitude and phase angle of the resulting complex function ($G(i\omega)$) are the amplitude ratio and phase angle of the system, for all values of ω. Thus, having the transfer function, the frequency response can be obtained or vice-versa.

This method of dynamic analysis was developed originally for the study of the stability of electrical and mechanical vibrating systems. In chemical systems, however,

stability is most often not of primary concern and frequency analysis is used as a means for checking or determining a model of the system.

As indicated in Chapter I a complete model of a double-effect evaporator would involve numerous simultaneous non-linear differential equations. Since neither the analytical nor numerical solution of these equations is practical some simplifications are necessary in order that the model have some utility. The most obvious method of simplification involves the elimination of differential equations which do not contribute significantly to the description of the dynamic response of the system. However some difficulty arises in comparing the contributions of the various equations.

The most satisfactory method of comparison involves the determination of the eigen values and eigen vectors for the linearized set of equations. Analysis of the solution expressed in terms of these quantities should indicate those elements of the system which dominate the dynamic response. Unfortunately, in view of the anticipated wide variation in the eigen values, the matrix pertaining to the linearized set of equations will be ill-conditioned(14).

An alternate, though intuitive approach, commonly used for the dynamic analysis of chemical processes (1,5) involves substitution of steady state equations for first

order differential equations displaying small time constants. For this purpose the time constant of a linearized equation is defined as the ratio of the coefficient of the first order term to the zero order term. This approach is based upon the assumption that the dynamic response of the element described by the differential equation is characterized by its time constant.

Considerable caution must be exercised in the application of this technique since interaction between the elements may be such that the individual time constants do not adequately represent the dynamic behavior of the associated elements. The final justification of this method of model simplification must rely on experimental analysis and may in fact only apply to the particular system involved in the investigation.

In order to obtain representative time constants for non-linear differential equations the equations must first be linearized. The method used to establish these time constants is illustrated in the following example. Consider a general differential equation of the type

$$\frac{dx}{dt} = f(x,y)$$

where $f(x,y)$ may be non-linear. If the Taylor's series of $f(x,y)$ can be obtained, then the equation can be written as

$$\frac{dx}{dt} = f_o(x_o y_o) + \left.\frac{\partial f}{\partial x}\right|_o (x - x_o)$$

$$+ \left.\frac{\partial f}{\partial y}\right|_o (y - y_o) + \text{higher order terms}$$

where x_o and y_o are steady state values.

If x and y are only slightly different from x_o and y_o then the higher order terms will be small compared to the first order terms and may thus be neglected. Therefore,

$$\frac{dx}{dt} = f_o(x_o,y_o) + \left.\frac{\partial f}{\partial x}\right|_o (x - x_o)$$

$$+ \left.\frac{\partial f}{\partial y}\right|_o (y - y_o)$$

is linear with a time constant

$$\tau = - \frac{1}{\left.\frac{\partial f}{\partial x}\right|_o}$$

Thus, in general, for any differential equation which can be approximated by a Taylor's series

$$\tau = - \left[\frac{\partial f(x,y,z,\ldots)}{\partial x}\right]^{-1}$$

III. LITERATURE REVIEW

As mentioned in Chapter I, to date, there has been little published work on the dynamics of evaporators. An extensive literature search yielded only three papers dealing with this subject.

The earliest of these papers was by D.E. Johnson(13), in which he describes the efforts made in analyzing the control of a single-effect falling-film evaporator in use in a Shell Chemical urea plant. Prior to the construction of this evaporator he conducted an analog study using a postulated transfer function, consisting of a dead time to relate flow out of the evaporator to flow in and integration to relate flow out to level. In spite of this rather simple model, he was able to recommend a constructive design change, namely that the pipe size at the bottom of the evaporator be enlarged.

However, when the evaporator was brought into operation, the original control scheme suggested did not function properly. Therefore, a test program was undertaken to determine the frequency response of temperature, vacuum and level to changes in feed flow, product flow, steam flow and air flow, the latter being used to control the vacuum produced by a steam ejector. His comments on the program include, "the data were extremely difficult to get and to analyze". Never-the-less the data were obtained and from these data more complete transfer functions were derived.

The most significant result obtained from these new transfer functions was that a very strong interaction existed between the vacuum and the evaporator level. For example "a 0.1 inch of mercury vacuum change caused at least an 8.5 inch level change over the entire test-frequency range". Using this result he recommended that a more sensitive vacuum control system be installed and that a pressure regulator be put on the steam line to the ejector.

Although this paper provides good evidence as to the worth of dynamic studies, the method used in achieving the final goal is questioned. It is felt that the approach taken in the present work, namely describing the dynamics by writing transient material and enthalpy balances on the process, based upon a knowledge of the physics involved, is to be preferred to postulating empirical equations to describe experimental data. The first method gives one more of an insight into the workings of the process and in some cases the dynamic significance of various sections or parameters of the process can be predetermined without testing. Also models arising from theoretical considerations are more easily altered to describe similar processes of different size or at different conditions. Another major criticism of the empirical method is the labor and lost or off-specification production involved. Without any insight into the significance of various parameters of the process the testing program must be comprehensive enough

to insure that all pertinent parameters are examined. This would inevitably result in the production of some data that in the final analysis proves to be unnecessary. Furthermore, for industrial sized equipment with large time constants, this testing program could take weeks to complete.

The method of developing a model from transient enthalpy and material balances was the method used by Andersen, Glasson and Lees(1) in their study of the dynamics of a single-effect calandria type evaporator. The model they developed consisted initially of six differential equations and four algebraic equations containing some fifty parameters. These equations were linearized by considering perturbations about steady state, then laboriously combined into four, quite complicated differential equations. Substituting numerical values for the parameters that made up the time constants of these equations showed that the time constant pertaining to the steam side of the calandria was negligible and the time constant for the metallic portion of the calandria was very small. Using this information the equations were reduced to three relatively uncomplicated differential equations.

To test this model they determined the frequency response of the product composition to feed flow changes, at a constant steam rate. The period of the feed flow oscillation was varied from 6 to 150 minutes, with best data being obtained

to suggest that all application parameters are important. This would seriously result in the preparation of some data that in the final analysis proves to be unnecessary. Furthermore, the industrial sized equipment into large time constants: this testing program would take nearly to complete.

The method of developing a model from theoretical reasoning and material balances was the method used by Anderson, Glasgow and Lessells in their study of the dynamics of a single-effect calandria type evaporator. The model they developed consisted initially of six differential equations and four algebraic equations containing some fifty parameters. These equations were linearized[7] by considering perturbations about steady state; and (preliminary) converted into less complicated differential equations. Substituting numerical values for the parameters and made up the time constants of these equations showed that the time constant relating to the steam side of the calandria was negligible and the time constant for the smaller portion of the calandria was very small. Using this information the equations were reduced to three relatively uncomplicated differential equations.

To test this model they perturbed the (flowrate) steam of the product composition by feed flow changes, or a constant steam flow. The period of the feed flow oscillations was varied from 4 to 100 minutes, with some runs being performed

for periods between 30 and 60 minutes. Noise was excessive at shorter periods and drifting from steady state created a problem at larger periods. The experimental and theoretical data were compared on a Bode plot (amplitude ratio and phase difference versus frequency) and showed a fair degree of scatter, especially the phase difference.

This paper gives a good indication of the labor required to test a model via frequency analysis. Their experimental program took five weeks to complete and then the data were somewhat inconclusive. Furthermore, their data covered only a limited portion of the Bode plot since the above-mentioned experimental difficulties prevented them from obtaining data at frequencies low enough to observe a corner point. They mention one attempt to test the model by way of the transient response to a step input but state only that the results were inconclusive.

It is felt that the development of the model for this evaporator would have been less laborious had the various sections of the evaporator been considered independently. For instance, the steam side of the calandria can be considered to be a separate module being acted upon by a steam flow rate and the calandria wall temperature. The only variable of significance to the rest of the evaporator is the steam temperature. Analysis of the equations describing this model shows that the response of temperature to disturbances is very rapid and thus from the onset the steam chest could

have been described by an algebraic equation. The walls of the calandria and solution in the evaporator can also be analyzed as separate modules.

The only paper located dealing with the dynamics of multiple-effect evaporators is that by Manczak(19). This paper describes the development of a model for a four-effect calandria type evaporator. In the derivation of his model a considerable amount of attention is given to the dynamics of steam in the chest of each effect. As mentioned above Andersen et. al. have shown that the response of the steam chest has a negligible effect on the system. This same conclusion was reached during the present study. Manczak also linearizes the resulting equations but in a manner that this author finds questionable. The steam temperature, which is in fact the most significant parameter, is considered by Manczak to be a constant during the linearization of the differential equations describing the steam chest. Furthermore, he does not present any results to support his transient model. Consequently a quantitative evaluation of his model is not possible.

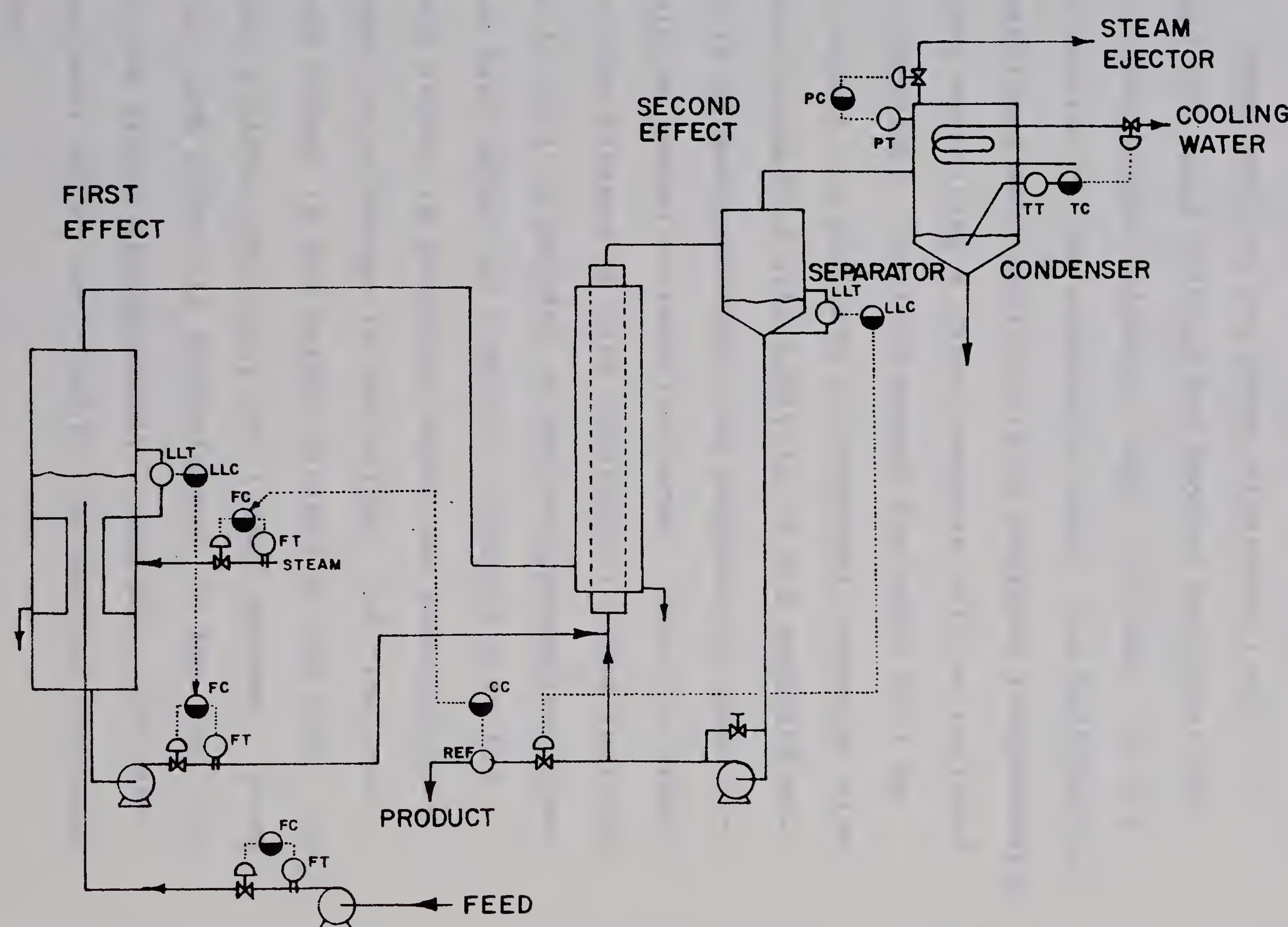
IV. MODEL DEVELOPMENT

Before proceeding with the development of the model it will be helpful to consider the simplified schematic diagram of the evaporator (Figure 1) as it was utilized for these experiments. As can be seen, the evaporator was operated in a feed-forward or parallel flow configuration. The reason for utilizing this control configuration will be explained in Chapter V.

The steam chest of the first effect was constructed in the shape of an annulus with the heating tubes around the outside and a downcomer in the middle to complete the circulation path. Feed is introduced at a point in the liquid above the steam chest, by a tube extending up from the bottom, and product is drawn off from the bottom.

The product from the first effect is pumped to the second where it mixes with the recirculation stream of the second effect. The mixed stream passes up the heating tubes of the second effect into a cyclone separator. The vapor is driven into the condenser and the liquid returns to the pump to be recirculated, with some being drawn off as product. The condenser was held at a fixed vacuum by a pressure controller. Condenser cooling water was controlled at a temperature low enough to insure that vapor losses through the vacuum line were negligible.

FIGURE I EVAPORATOR AND CONTROLS — SIMPLIFIED SCHEMATIC



As mentioned earlier, for modelling purposes, the evaporator was considered to be made up of several interacting modules. These modules are shown diagrammatically in Figure 2 where the lines joining the modules represent the transfer of either liquid solution, vapor, or heat. In the following derivation of the evaporator model, the differential equations describing each module will be analyzed independently. Those equations exhibiting a rapid response will be replaced by algebraic equations. In this manner the model will be simplified to permit its solution in reasonable computer time.

Before proceeding with analysis of the separate modules it should be mentioned that the response of these modules can only be judged in relative terms. Thus, in order to judge the significance of time constants for the individual sections it will be helpful to derive hypothetical time constants for each effect as a whole. Assuming that the liquid in each effect is perfectly mixed and assuming further that there is no change in the holdup, the time constant for each effect is the holdup divided by the flow. This is, of course, strictly true only for linear systems. Since the holdup for each effect is approximately 30 lbs. and the feed rate to the system approximately 3 lbs/min., the time constants for each effect are roughly the same and are equal to 10 minutes.

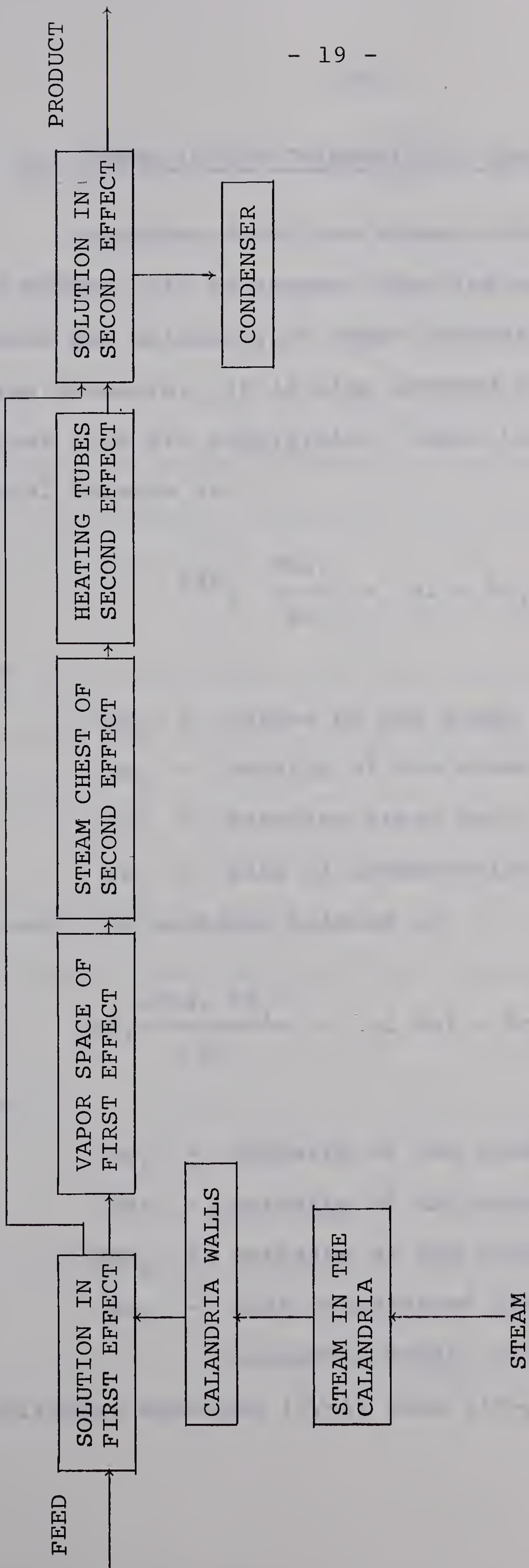
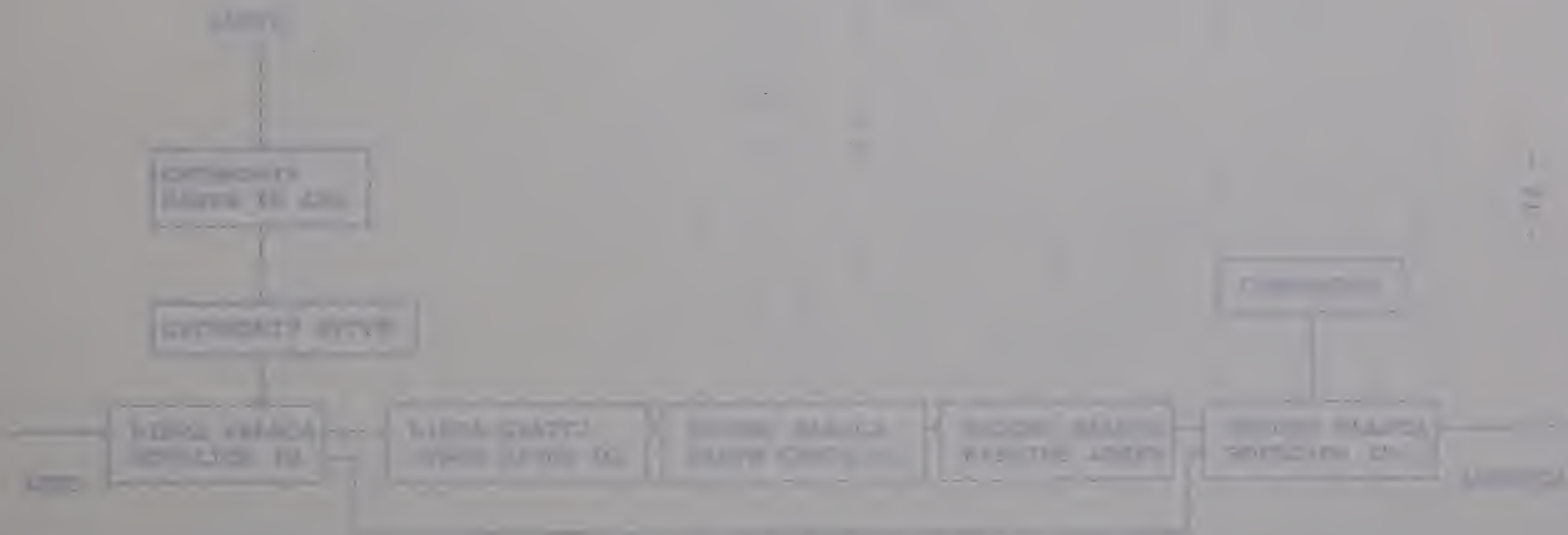


Figure 2

Evaporator - Block Diagram



A. Steam in the Calandria of the First Effect

Consider first the steam in the calandria of the first effect. It is assumed that the steam and condensate produced are uniformly at their saturation point for the prevailing pressure. It is also assumed that condensate holdup and heat loss are negligible. Under these assumptions the material balance is

$$Vsc_1 \frac{dDs_1}{dt} = Si - Sc_1 \qquad \text{(IV-1)}$$

where

Vsc_1 = volume of the steam space, ft.^{3}

Ds_1 = density of the steam in the chest, lbs/ft.^{3}

si = entering steam rate, lbs/min.

Sc_1 = rate of condensation, lbs/min.

Similarly the enthalpy balance is

$$Vsc_1 \frac{d(Ds_1\ Hs_1)}{dt} = Si\ Hsi - Sc_1\ Hsc_1 - Qs_1 \qquad \text{(IV-2)}$$

where

Hs_1 = enthalpy of the steam in the chest, btu/lb.

Hsi = enthalpy of the entering steam, btu/lb.

Hsc_1 = enthalpy of the condensate, btu/lb

Qs_1 = heat transferred from the steam to the calandria walls, btu/min.

Substituting equation (IV-1) into (IV-2) yields

$$Vsc_1(Ds_1 \frac{dHs_1}{dt} + (Hs_1 - Hsc_1) \frac{dDs_1}{dt}) = Si(Hsi - Hsc_1) - Qs_1 \quad \text{(IV-3)}$$

For the temperatures encountered in this work the enthalpies of steam and water can be represented by

$$Hs_1 = 1066. + 0.4\, Ts_1 \quad (Ts_1 \text{ in } {}^{\circ}F)$$

$$Hsc_1 = -32. + 1.0\, Ts_1 \quad (Ts_1 \text{ in } {}^{\circ}F)$$

where Ts_1 is the saturated steam temperature. Assuming that a spatially averaged temperature, Tw_1, can be associated with the calandria wall, then

$$Qs_1 = hs_1 A_1 (Ts_1 - Tw_1)$$

where hs_1 is the steam side film coefficient as A_1 is the heat transfer area. Further, since the steam is assumed to be saturated

$$Ds_1 = f(Hs_1) = f(Ts_1)$$

Assuming a linear relationship of the form $Ds_1 = \alpha Ts_1 + \beta$ and substituting this along with the above expressions into (Iv-3)

$$\frac{dTs_1}{dt} = \frac{Si(Hsi + 32. + 1.Ts_1) - hs_1 A_1\ (Ts_1 - Tw_1)}{Vsc_1(.4Ds_1 + \alpha(1098. - .6Ts_1))} \quad \text{(IV-4)}$$

It has been shown in Chapter II that the time constant for the linearized version of equation (IV-4) is

$$\tau = -\left(\frac{\partial}{\partial Ts_1} \frac{dTs_1}{dt}\right)^{-1}$$

Performing the operation specified by this equation yields

$$\tau = \frac{Vsc_1(.4Ds_1 + \alpha(1098. - .6Ts_1))}{Si + hs_1A_1}$$

Substituting the following average steady state values

$$Si = 1.0 \text{ lbs/min.}$$

$$Vsc_1 = .4 \text{ ft}^3$$

$$hs_1A_1 = 235 \text{ btu/min } {}^{\circ}\text{F (Appendix 12)}$$

$$Ds_1 = .0433 \text{ lbs/ft}^3$$

$$\alpha = .00075 \text{ lbs/}{}^{\circ}\text{F ft}^3$$

$$Ts_1 = 220^{\circ}\text{F}$$

yields

$$\tau = 1.27 \times 10^{-3} \text{ mins.}$$

Therefore, the response of steam temperature to disturbances is very rapid. This means that for any change the new steady state is achieved rapidly which is tantamount to saying the right-hand-side (RHS) of equations (IV-1) and (IV-2) are always equal to zero. Thus,

$$Sc_1 = Si$$

and

$$Si(Hsi - Hsc_1) = Qs_1$$

Substituting for Qs_1 and Hsc_1 in equation (IV-5) and rearranging results in the following equation.

$$Ts_1 = \frac{Si(Hsi + 32.) + hs_1A_1Ts_1}{1.0\ Si + hs_1A_1} \qquad \text{(Iv-6)}$$

Equation (IV-6) completely characterizes the steam in the calandria of the first effect.

B. Calandria Walls

Next consider a heat balance on the metal of the calandria. It is assumed that temperature gradients in the metal of the calandria are negligible.

$$Wsc_1 Cpsc_1 \frac{dTw_1}{dt} = hs_1 A_1 (Ts_1 - Tw_1) - h_1 A_1 (Tw_1 - T_1) \quad \text{(IV-7)}$$

where

Wsc_1 = weight of the calandria = 97 lbs.

$Cpsc_1$ = heat capacity of the calandria metal = .12 btu/lbs. $^{\circ}F$

h_1 = heat transfer coefficient for the solution side of the calandria, btu/min. ft^2 $^{\circ}F$

T_1 = temperature of the solution in the first effect evaluated from the enthalpy and concentration, $^{\circ}F$

Assuming that the heat transfer coefficients are constant, the time constant for the calandria is

$$\tau = \frac{Wsc_1 Cpsc_1}{hs_1 A_1 + h_1 A_1}$$

The average of $h_1 A_1$ is 78.2 btu/min.$^{\circ}F$ (appendix 12). When this and other numerical values are substituted into equation

(IV-8) the time constant is found to be

$$\tau = \frac{97. \times .12}{235 + 78.2} = 0.04 \text{ min.}$$

Consequently the time lag involved in transferring heat from the steam to the solution in the first effect is negligible. Therefore the heat transferred can be defined as

$$Qs_1 = U_1A_1(Ts_1 - T_1) \tag{IV-9}$$

where

U_1 = overall heat transfer coefficient, btu/min.ft^2 ^oF

T_1 = temperature of the solution in the first effect, ^oF

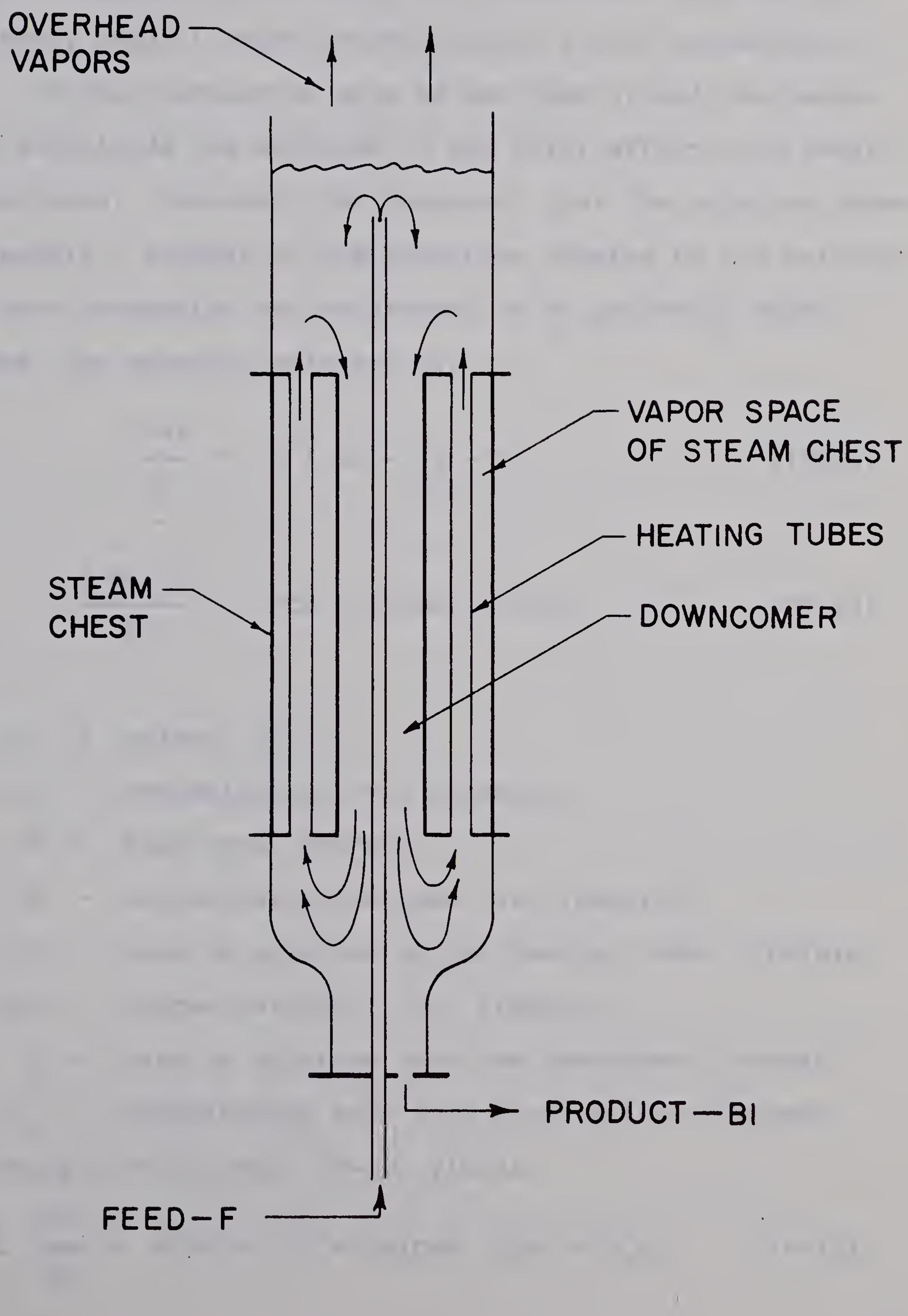
Thus, equation (IV-6) is changed to the following

$$Ts_1 = \frac{Si(Hsi - 32.) + U_1A_1T_1}{1.0\ Si + U_1A_1} \tag{IV-10}$$

C. Solution in the first Effect

Consider now the diagram of the first effect shown in Figure 3. For this effect, as indeed for most chemical processes, a very important parameter of the dynamics is the rate of mixing, which in this situation is directly related to the circulation rate. For most evaporators the rate of circulation is probably high enough to ensure essentially perfect mixing of the liquid effected. But it is realized that for

FIGURE 3 SCHEMATIC OF THE FIRST EFFECT



viscous solutions, or low boiling rates or constricted passages or a combination of these, the circulation rate may be sufficiently small to make perfect mixing a poor assumption.

If the circulation rate is low then it will be necessary to sub-divide the solution in the first effect into several subsections. Consider, for instance, just the solution above the calandria. Because of the agitation created by the boiling action this subsection can be assumed to be perfectly mixed. Therefore, the material balances are

$$\frac{dWi}{dt} = F + Ut - O_1 - D \qquad \text{(IV-11)}$$

$$\frac{d\,Wi\,Ci}{dt} = FCf + Ut\,Cut - D\,Ci \qquad \text{(IV-12)}$$

where

Wi = holdup, lbs.

Ci = concentration, wt. fraction

F = feed rate, lbs/min.

Cf = concentration of feed, wt. fraction

Ut = rate of solution up the heating tubes, lbs/min.

Cut = concentration Ut, wt. fraction

D = rate of solution down the downcomer, lbs/min.

O_1 = vaporization rate from first effect, lbs/min.

Substituting (IV-11) into (IV-12) yields

$$Wi\,\frac{dCi}{dt} = F(Cf - Ci) + Ut(Cut - Ci) + O_1Ci \qquad \text{(IV-13)}$$

The time constant of equation (IV-13) is

$$\tau = \frac{Wi}{Ut + F - O_1} \qquad \text{(IV-14)}$$

Experimental average values for Wi, F and O_1 are

$$Wi = 10 \text{ lbs.}$$

$$F = 3 \text{ lbs./min.}$$

$$O_1 = 1 \text{ lb/min.}$$

Therefore,

$$\tau = \frac{10}{Ut + 2} \qquad \text{(IV-15)}$$

Thus, in order to determine a numerical value for this time constant a value for the circulation (Ut) is also required.

To achieve this goal a method for determining the circulation rate in natural circulation systems presented by Lottes and Flinn(18) was used. The equation they presented, with experimental verification, is

$$(\rho f - \bar{\rho})Lb = \frac{Vin^2 \rho f}{2\, gc} \left(\frac{fo\ Le}{Dt} + \frac{\bar{R}\ fo\ Lb}{Dt} + 2\, \bar{r}\, \rho f \right) \qquad \text{(IV-16)}$$

where

ρf = liquid density, lbs./ft^3

$\bar{\rho}$ = bulk density of liquid-vapor mixture, lbs./ft^3

Lb = length of boiling section of tube, ft.

Vin = inlet liquid velocity, ft./min.

Dt = diameter of tube, ft.

Le = equivalent length of tube, ft.

fo = Fanning friction factor

$\overline{R}, \overline{r}$ = correction factors

Recognizing that $(\rho f - \rho)Lb$ is the hydrostatic head causing flow through the heating tubes, it is seen that equation (IV-16) is the standard Fanning equation with correction terms added. The term containing $\overline{R}$ corrects for the difference between two-phase and single-phase friction losses and the term containing $\overline{r}$ corrects for pressure losses due to the acceleration of the fluid. Values for $\overline{\rho}$, $\overline{R}$, and $\overline{r}$ were presented in terms of parameter α, equal to the vapor volume fraction at the tube exit. This parameter is in turn related to the vapor weight fraction, a quantity which can be calculated if the inlet velocity and vapor production rates are known. Lottes and Flinn presented this relationship in terms of experimental data which was unfortunately out of the range of interest for this system. However, an article by Levy(16) was located in which he presented an experimentally verified equation (equation (IV-17)) relating vapor void fraction and weight fraction.

$$\alpha = \frac{4X^2Z - (1-X)^2 - (1-X)\sqrt{(1-X)^2 + 8X^2Z}}{4(X^2Z - (1-X)^2)} \qquad \text{(IV-17)}$$

where

α = vapor volume fraction

X = vapor weight fraction

Z = ratio of liquid density to vapor density

Thus, using equations (IV-16) and (IV-17) the inlet velocity to a single heating tube could be calculated. A program to perform the necessary trial and error calculations was written and used to calculate the inlet velocity for a wide variety of conditions that might be encountered in this evaporator. This program is illustrated in Appendix 3. In all situations the inlet velocity remained very close to 130 ft./min. Since there are 32 heating tubes in the first effect calandria, each being 3/4 inch in diameter, the circulation rate through the steam chest is approximately 556 lbs./min.

Substituting this value into equation (IV-15) the time constant pertaining to the solution above the calandria is

$$\tau = \frac{10}{556} = .018 \text{ min.}$$

In comparison to the solution in the first effect as a whole, the transient response of the liquid above the calandria is very rapid. Furthermore it can be shown that the time constants pertaining to other subsections of the evaporator (downcomer, solution below the calandria, etc.) are of the same order of magnitude as the above. Therefore, it can be assumed that the solution in the first effect as a whole is perfectly mixed. Thus, the equations describing the first effect solution are

$$\frac{dW_1}{dt} = F - B_1 - O_1 \qquad \text{(IV-18)}$$

$$\frac{dW_1H_1}{dt} = FHf - B_1H_1 - O_1Ho_1 + Q_1 - HL_1 \qquad \text{(IV-19)}$$

$$\frac{dW_1C_1}{dt} = FCf - B_1C_1 \qquad \text{(IV-20)}$$

where

W_1 = solution holdup first effect, lbs.

B_1 = solution product rate first effect, lbs./min.

Hf = feed enthalpy, btu/lb.

H = enthalpy of first effect solution, btu/lb.

Ho_1 = enthalpy of first effect vapor, btu/lb.

HL_1 = heat loss from first effect, btu/min.

Q_1 = heat addition to first effect, btu/min.

Cf = feed concentration, wt. fraction

C_1 = concentration of first effect solution, wt. fraction

D. Vapor Space of the First Effect and the Steam Chest of the Second

For both of these volumes it is assumed that the vapor present is uniformly at its saturation point for the prevailing pressure. However, since a pressure potential is required to drive the vapor from the first effect to the second effect, the pressure in each volume will in general be different.

For this evaporator the vapor line between the two effects is a 2-inch glass pipe, eight feet in length, with two elbows, to give it an approximate equivalent length of 30 feet. Using the Fanning equation and approximate average values for density and flow, the pressure drop across the vapor line is

$$\Delta P = \frac{8f\ Le\ W^2}{gc\ D^3\ \rho}$$

where

W = evaporator flow rate = 1 lb/min.

Le = equivalent length = 30 ft.

f = Fanning friction factor = .0093

D = pipe diameter = 2 inches

ρ = vapor density = .027 lbs/ft^3

and therefore,

$$\Delta P = 0.001 \text{ psi}$$

Thus, for this evaporator the pressure in the first effect and pressure in the steam chest of the second effect are essentially equal. Furthermore, since it is assumed that the vapor in both of these volumes is saturated, they may be considered to be a single unit. Assuming that the condensate holdup is negligible, the equations that describe the transient behavior of the vapor in these volumes are

$$Vv_1 \frac{dDv_1}{dt} = O_1 - Sc_2 \qquad \text{(IV-21)}$$

$$Vv_1 \frac{dDv_1Hv_1}{dt} = O_1Ho_1 - Sc_2Hsc_2 - Q_2 + HL_2 \qquad \text{(IV-22)}$$

where

Dv_1 = density of the vapor, lbs./ft^3

Vv_1 = volume occupied by the vapor, ft^3

Sc_2 = condensation rate in the second effect, lbs./min.

Hv_1 = enthalpy of the vapor, btu/lb.

Hsc_2 = enthalpy of the condensate, btu/lb.

Q_2 = heat transfer rate in the second effect, btu/min.

HL_2 = heat loss from the vapor line and steam chest of the second effect, btu/min.

It is seen that these two equations are analagous to equations (IV-1) and (IV-2) describing the transient behavior of the steam in the first effect calandria. Thus, it can be shown, in exactly the same manner as was done for equations (IV-1) and (IV-2), that the response of the above two equations is relatively very rapid and they may therefore be replaced by the algebraic steady state equations

$$O_1 = Sc_2$$

$$O_1(Ho_1 - Hsc_2) = Q_2 + HL_2$$

However, since condensate holdup is assumed to be negligible

$$Sc_2(Hv_1 - Hsc_2) = Q_2 + HL_2$$

and therefore,

$$Ho_1 - Hsc_2 = Hv_1 - Hsc_2 \qquad \text{(IV-22)}$$

Equation (IV-22) means that the enthalpy of the vapor leaving the boiling solution of the first effect, Ho_1, is equal to the enthalpy of the vapor in the steam chest of the second effect, Hv_1. Therefore, since boiling-point rise is negligible for the sugar-water solutions used in these experiments, the temperature of this vapor is equal to the temperature of the liquid in the first effect, T_1.

Therefore, the rate of evaporation from the first effect is

$$O_1 = \frac{(Q_2 + HL_2)}{Hev_1} \qquad \text{(IV-23)}$$

where Hev_1, the latent heat of evaporation, is evaluated at T_1, the temperature of the first effect solution.

E. Heating Tubes of the Second Effect

In this evaporator the heat transfer coefficients, heat transfer area and weight of metal are of the same order of magnitude for both effects. Since these are the parameters that determine the transient response of the metallic portions of each steam chest, it is assumed that, as in the first effect, the response of the second effect heating tubes is rapid. Therefore, the heat transfer rate may be expressed in terms of an overall heat transfer coefficient. That is,

$$Q_2 = U_2A_2(T_1 - T_2) \qquad \text{(IV-24)}$$

where

U_2 = overall heat transfer coefficient, btu/min.ft^3 ^oF

A_2 = heat transfer area of the second effect, ft^2

T_2 = temperature of the second effect solution, ^oF

F. Solution in the Second Effect

For the second effect about one half, or approximately 10 lbs., of the total liquid holdup is in the cyclone separator and the rest is in the pump, evaporator tubes and connecting lines. However, in view of the fact that the circulation rate is approximately 200 lbs./min., the entire holdup is considered to be a perfectly mixed unit. Thus, the equations describing the second effect are

$$\frac{dW_2}{dt} = B_1 - B_2 - O_2 \qquad \text{(IV-25)}$$

$$\frac{dW_2C_2}{dt} = B_1C_1 - B_2C_2 \qquad \text{(IV-26)}$$

$$\frac{dW_2H_2}{dt} = Q_2 + B_1H_1 - B_2H_2 - O_2Ho_2 - HL_3 \qquad \text{(IV-27)}$$

where the subscript 2 refers to second effect properties and HL_3 is the combined heat loss from the circulating liquid and

product stream from the first effect (B_1).

As mentioned in the early part of this chapter, the pressure in the final condenser was under control and since the separator is connected to the condenser by a short 3-inch diameter glass pipe, the pressure in the cyclone and condenser are essentially equal, at a value determined by the controller action. Now it can be shown, in a manner completely analogous to that used for the first effect, that the temperature of the vapor in the cyclone is equal to the liquid temperature and since the vapor temperature is its saturation temperature for the prevailing pressure, the temperature of the liquid in the second effect (T_2) is determined completely by the action of the pressure controller on the condenser.

Therefore, since enthalpy is a function of concentration and temperature, equation (IV-27) above is redundant. Substituting equation (IV-25) into (IV-26) and (IV-27) yields

$$\frac{dC_2}{dt} = B_1(C_1 - C_2) + O_2C_2 \qquad \text{(IV-28)}$$

$$\frac{dH_2}{dt} = Q_2 - HL_3 + B_1(H_1 - H_2) - O_2(Ho_2 - H_2) \qquad \text{(IV-29)}$$

but since $H_2 = f(C_2, T_2)$

$$\frac{dH_2}{dt} = \frac{\partial H_2}{\partial C_2}\,\frac{dC_2}{dt} + \frac{\partial H_2}{\partial T_2}\,\frac{dT_2}{dt} \qquad \text{(IV-30)}$$

For convenience of notation, let

$$\frac{\partial H_2}{\partial T_2} = X$$

$$\frac{dT_2}{dt} = Y$$

$$\frac{\partial H_2}{\partial C_2} = Z$$

Substituting equations (IV-28) and (IV-29) into equation (IV-30) yields

$$XY + ZB_1(C_1 - C_2) + ZO_2C_2 = Q_2 - HL_3 + B_1(H_1 - H_2) - O_2(Ho_2 - H_2)$$

which can be rearranged to give the following expression for O_2:

$$O_2 = \frac{Q_2 - HL_3 + B_1(H_1 - H_2) + ZB_1(C_2 - C_1) - XY}{Ho_2 - H_2 + ZC_2} \qquad \text{(IV-31)}$$

Equation (IV-31) along with the material and concentration balances thus define the transient behavior of the second effect.

Upon closer analysis of these equations describing the second effect it is seen, that as written, there is an implied assumption, namely that the transport lag between the first and second effect is negligible. For the majority of the experiments conducted in this work this assumption is probably valid, but since the model was solved on a digital computer,

the addition of transport lag was relatively simple. Denoting with a prime the properties of the stream entering the second effect, the following equations describe the transport lag.

$$C_1'(t) = C_1(t - d)$$

$$H_1'(t) = H_1(t - d)$$

where d is the transport lag and is

$$d = \frac{Ap\ Lp\ \rho}{B_1}$$

Ap = average area of the line between the first and second effects = 3.4×10^{-3} ft^2

Lp = length of the line between the first and second effects = 19 ft

ρ = density of the flowing stream = 62 lbs/ft^3

Assuming a constant density, the time delay for this evaporator is

$$d = \frac{4.0}{B_1}$$

G. Condenser

It is seen in Figure 1 that there are two control loops associated with the condenser. One loop controls the pressure in the condenser and the other regulates the cooling water rate in the condenser coils to control the condensate temperature.

It is acknowledged that for minimum cooling water consumption the condensate temperature should be controlled at or near the saturation temperature corresponding to the pressure of the condenser. But when this was attempted there was considerable interaction between the control loops. This interaction made it impossible to maintain a pressure free from periodic fluctuations. Moreover, these fluctuations, for reasons that will be explained in Chapter VIII, were very disrupting to the system. Therefore, the condensate was sub-cooled approximately $20^{\circ}F$ and in this manner a steady condenser pressure was achieved. Being operated in this fashion, the condenser, so far as the rest of the evaporator was concerned, behaved essentially as a constant-pressure condensate sink. This constant pressure thus produced a constant temperature in the solution in the second effect.

H. Controllers

Except for enthalpy data and numerical values for the system parameters, all that is required for completion of the model are equations describing the control action. The controllers shown in Figure 1 are all Foxboro electronic, proportional plus reset controllers with the concentration controller having rate action as well. It is assumed that all valves and transmitters respond rapidly and that the controllers behave ideally. That is, the action of a proportional-reset-rate controller is described by

$$m = Kc\left(e + \frac{1}{Ti}\int edt + Td\frac{de}{dt}\right) + mo$$

where

Kc = proportional constant

Ti = integral time

Td = rate time

e = error signal

m = controller output signal

mo = controller output signal at steady state

Referring to Figure 1, it is seen that the product stream from the first effect (B_1) is controlled by a flow controller whose set point is established by the liquid level controller of the first effect. The equations describing this flow controller are

$$Cb_1 = \frac{100.}{Kb_1}\left(Eb_1 + \frac{1}{Tb_1}\int Eb_1 dt\right) + \overline{Cb_1}$$

where $Eb_1 = L_1 - Fb_1$ and

Cb_1 = output of flow controller, 0 - 100%

Kb_1 = proportional band, 0 - 100%

Tb_1 = integral or reset time, mins.

L_1 = output of level controller, 0 - 100%

Fb_1 = output of flow transmitter, 0 - 100%

For the purpose of establishing the dynamic response of this control-loop it is assumed that the output of the flow transmitter is linear with regards to flow and that the relationship

between controller output (Cb_1) and flow is linear, i.e.

$$Fb_1 = Kft\ B_1 + \text{constant}$$

$$B_1 = Kv_1 Cb_1 + \text{constant}$$

where Kft and Kv_1 are the proportionality constants. Substituting these expressions into equation (IV-32) yields

$$B_1 = \frac{100.\ Kv_1}{Kb_1}\left[L_1 - Kft\ B_1 + \frac{1}{Tb_4}\int (L_1 - Kft\ B_1 - \text{const.})dt\right] + \text{constant} \qquad \text{(IV-33)}$$

Differentiating equation (IV-33) and extracting the characteristic equation yields

$$(Tb_1 + \frac{Kb_1 Tb_1}{100.\ Kft\ Kv_1})\frac{dB_1}{dt} + B_1 = 0$$

The term in brackets is of course the time constant. For this work the values for the various parameters are

$$Kb_1 = 170\%$$
$$Tb_1 = .2 \text{ min.}$$
$$Kft = 29.7\%/\text{lb./min.} \quad \text{(Appendix 13)}$$
$$Kv_1 = .073 \text{ lbs./min./\%} \quad \text{(Appendix 13)}$$

Substituting these values into equation (IV-33) yields

$$.36\frac{dB_1}{dt} + B_1 = 0$$

Therefore, the response of this control loop is quite rapid and it can be assumed that the flow is always at its set point.

For the actual solution of the model the above approximate linear correlation between flow and flow-transmitter output need not be used since a more exact equation can be obtained. During this work the average correlation between flow and flow-transmitter output could be represented by

$$B_1 \approx .44(Fb_1)^{.48}$$

and therefore, since the flow is considered to be always at its set point,

$$B_1 = .44(L_1)^{.48}$$

where L_1 is the output of the first effect level controller.

The equation describing the level control of the first effect is

$$L_1 = \frac{100.}{KL_1}(EL_1 + \frac{1}{TL_1}\int EL_1 dt) + \overline{L_1} \qquad \text{(IV-34)}$$

where EL_1 is the error signal and KL_1 and TL_1 are the controller settings. If $\overline{W_1}$ is the liquid holdup in the first effect when the level is at its set point then

$$EL_1 = KLt_1 \frac{(W_1 - \overline{W_1})}{Ax_1 \, \rho w} \qquad \text{(IV-35)}$$

where

Ax_1 = x-section area of first effect = .37 ft^2

ρw = density of water

KLt_1 = proportional constant of transmitter, %/ inches of water

The liquid level controller on the second effect is completely analogous to the above. That is,

$$L_2 = \frac{100.}{KL_2} (EL_2 + \frac{1}{TL_2} \int EL_2 dt) + \overline{L}_2 \qquad \text{(IV-36)}$$

and

$$EL_2 = \frac{KLt_2 (W_2 - \overline{W_2})}{Ax_2 \quad w}$$

However, for the second effect the liquid level controller output goes directly to the valve in the product line rather than to the set point of a flow controller. This valve is a Foxboro, model V-4 needle valve with parabolic plug, as are all valves on the evaporator. The valve characteristic for this type of valve can be expressed by

$$\% \text{ of maximum flow} = 10^{.424 + .0158v} \qquad \text{(IV-37)}$$

where v is the valve position in percent. If $\overline{B_2}$ is the flow rate at steady state and $\overline{v}$ the valve position, then

$$B_2 = \frac{B_2 max}{100} 10^{.424 + .0158v}$$

and

$$\overline{B_2} = \frac{B_2 max}{100} 10^{.424 + .158\overline{v}}$$

Dividing the first equation by the second yields

$$B_2 = \overline{B_2}\ 10^{.0158(v-\overline{v})}$$

Further, if the dynamic response of the valve motor is neglected then

$$B_2 = \overline{B_2}\ 10^{.0158(L_2-\overline{L_2})} \qquad \text{(IV-38)}$$

where $(L_2 - \overline{L_2})$ is the deviation in percent of the second effect level controller from its set point.

As can be seen in Figure 1, the composition of the second effect product acts through a controller to establish the set point of the flow controller for the steam to the first effect. This flow control loop is analogous to the flow control loop of the first effect product stream and it can be shown that it also may be assumed to be always at its set point. This set point is equal to Cc_2 the output of the concentration controller. Substituting Cc_2 into the equation describing the steam flow correlation curve for this evaporator yields

$$Si = .68\ SDENS\ (Cc_2)^{.455} \qquad \text{(IV-39)}$$

where SDENS is the square root of the flowing steams' density.

As mentioned earlier, the composition controller is a proportional-reset-rate controller and therefore the control action is approximated by

$$Cc_2 = \frac{100}{Kc_2}\left(Ec_2 + \frac{1}{Tc_2}\int Ec_2 dt + Tdc_2 \frac{dEc_2}{dt}\right) + \overline{Cc_2} \qquad \text{(IV-40)}$$

$$Ec_2 = Kr_2(\overline{C_2} - C_2)$$

where

$\overline{C_2}$ = desired product composition, wt. fraction

Kr_2 = proportionality constant of the composition transmitter, %/wt. fraction

Tdc_2 = derivative time of the controller, min.

Cc_2 = controller output at steady state, %

The transient behavior of the evaporator is unaffected by the action of the remaining controllers associated with the evaporator and therefore they need not be considered in the dynamic model.

I. Physical Parameters and Enthalpy Data

The only remaining requirements for completion of the model are data for pertinent physical parameters of the evaporator and data relating temperature, concentration and enthalpy for the sugar-water solution used.

The data for the pertinent parameters of the system are

A_1 = 9.3 ft^2

A_2 = 3.9 ft^2

Ax_1 = Ax_2 = 0.37 ft^2

KLt_1 = KLt_2 = 46.7 %/ft.H_2O

Kr_2 = 1000.

ρw = 62.4 lbs./ft^3

As will be pointed out later, the heat transfer coefficients and heat losses for each run were calculated from experimental data. Also, since the steam input conditions varied somewhat between experiments the steam enthalpy (Hsi) and square root of density (SDENS) were fed to the computer for each simulation.

For the enthalpy data a paper by Higbie(10) was referred to in which he presents the partial enthalpies of water and sugar in sucrose solutions for sugar concentrations up to 65% and for temperatures between 32°F and 200°F.

For concentrations between 0% and 15% and temperatures between 140°F and 200°F (the ranges applicable to this work) the following empirical equation was developed and used in this work

$$H = T(1. - .454C) + 6.C - 32.1$$

where C is the weight fraction of sugar. The enthalpies calculated from this equation were compared with enthalpies calculated using the Higbie's partially enthalpy data directly for all data points within the above ranges and in all cases the agreement was better than .1%.

J. Summary of Model

For convenience, the equations constituting the model of this evaporator, in summary are

$$\frac{dW_1}{dt} = F - O_1 - B_1 \qquad \text{(IV-18)}$$

$$\frac{dW_1H_1}{dt} = FHf + Q_1 - B_1H_1 - O_1Ho_1 - HL_1 \qquad \text{(IV-19)}$$

$$\frac{dW_1C_1}{dt} = FCf - B_1C_1 \qquad \text{(IV-20)}$$

$$\frac{dW_2}{dt} = B_1 - B_2 - O_2 \qquad \text{(IV-25)}$$

$$\frac{dW_2C_2}{dt} = B_1C_1' - B_2C_2 \qquad \text{(IV-26)}$$

$$Q_1 = U_1A_1(Ts_1 - T_1) \qquad \text{(IV-9)}$$

$$Ts_1 = \frac{Si(Hsi + 32.) + U_1A_1T_1}{U_1A_1 + 1.0\ Si} \qquad \text{(IV-10)}$$

$$T_1 = \frac{(H_1 + 32.1 - 6.\ C_1)}{(1. - .454\ C_1)}$$

$$O_1 = \frac{(Q_2 + HL_2)}{Hev_1} \qquad \text{(IV-23)}$$

$$Q_2 = U_2A_2(T_1 - T_2) \qquad \text{(IV-24)}$$

$$O_2 = \frac{Q_2 - HL_3 + B_1(H_1' - H_2) + ZB_1(C_2 - C_1')}{Ho_2 - H_2 - ZC_2} \qquad \text{(IV-31)}$$

$$B_1 = .44(L_1)^{.48}$$

$$L_1 = \frac{100.}{KL_1}\left(EL_1 + \frac{1}{TL_1}\int EL_1 dt\right) + \overline{L_1} \qquad \text{(IV-34)}$$

$$B_2 = \overline{B_2}\ \ 10^{.0158(L_2 - \overline{L_2})} \qquad \text{(IV-38)}$$

$$L_2 - \overline{L_2} = \frac{100}{KL_2}\left(EL_2 + \frac{1}{TL_2}\int EL_2 dt\right) \qquad \text{(IV-36)}$$

$$EL_2 = 2.05\ (W_2 - \overline{W_2})$$

$$Si = .68\ \text{SDENS}\ (Cc_2)^{.455} \qquad \text{(IV-39)}$$

$$Cc_2 = \frac{100}{Kc_2}\left(Ec_2 + \frac{1}{Tc_2}\int Ec_2 dt + Tdc_2 \frac{dEc_2}{dt}\right) + Cc_2 \qquad \text{(IV-40)}$$

$$Ec_2 = 1000.\ (\overline{C_2} - C_2)$$

V. EQUIPMENT

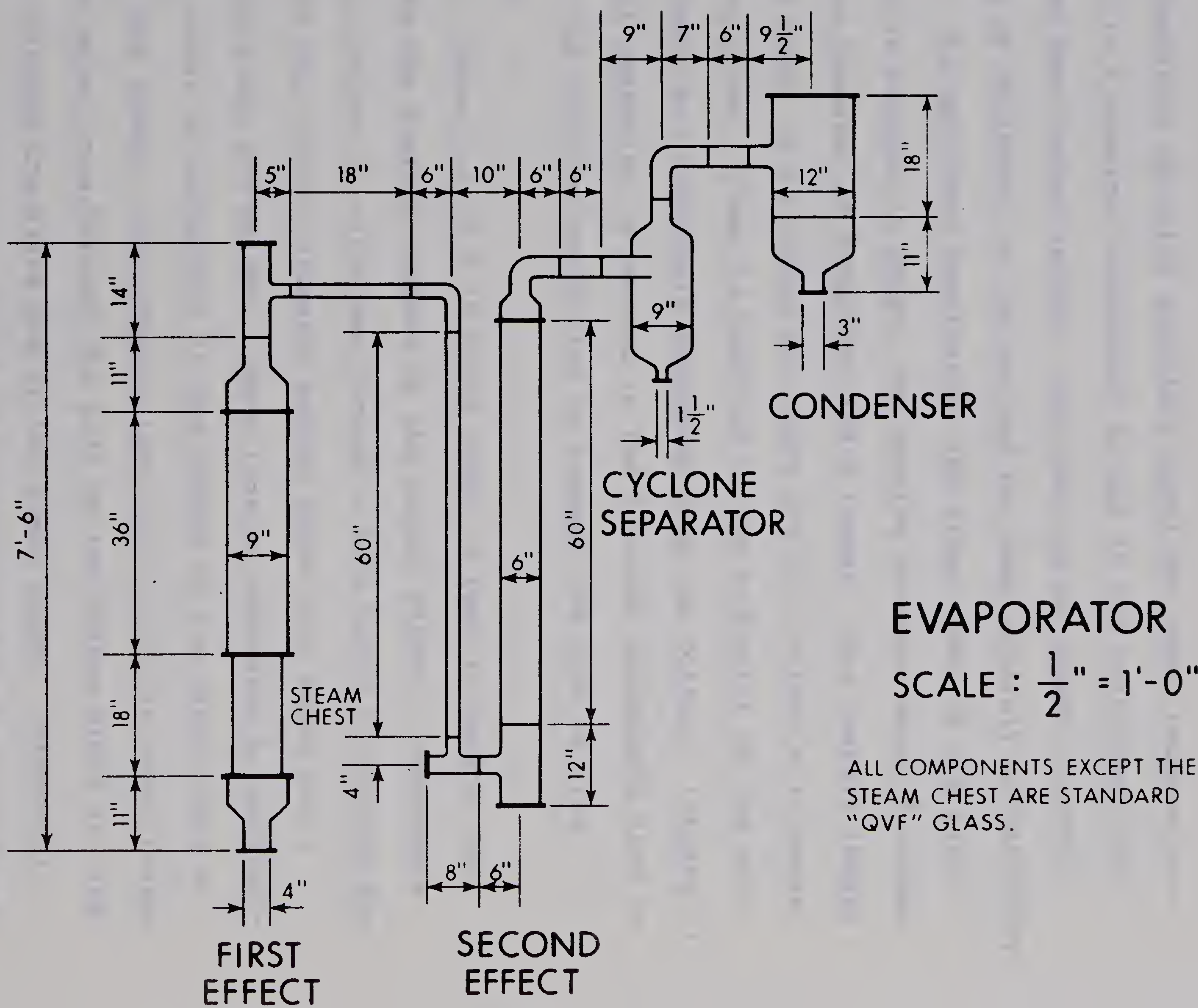
A. Basic Process

During the design of this evaporator no attempt was made to optimize the design nor to design to rigid specifications, rather it was hoped that the design would allow for a fairly wide range of operating conditions. However, in order to have a place to start, a feed flow rate of 100 lbs./hr. was assumed and the body size of each effect selected so as to give the evaporator overall time constants roughly equivalent to industrial sized evaporators.

The bodies of each effect are constructed of glass supplied from the standard inventory of QVF Glass Limited. The separator, condenser and vapor line between the first and second effects are also QVF glass. Figure 4 is a diagram of the glassware with its dimensions. Double lucite cylinders are mounted on the outside of the first effect glassware, the vapor line and the steam chest of the second effect to insulate against heat losses. The shape of the cyclone made it difficult to use lucite cylinders for insulation, so for the course of this work the cyclone was wrapped in fibre glass, a more satisfactory insulation to be added later.

Stainless steel, types 304 and 316, was used in the construction of all metal parts of the evaporator. Similarly all liquid lines were made from stainless steel pipe and tubing.

FIGURE 4 EVAPORATOR GLASSWARE



The precaution of using stainless steel was taken because corrosion in a previous evaporator in use in the unit operations lab had been rather severe. Also the use of copper on other pieces of equipment in the lab had not been entirely satisfactory.

As mentioned previously, the steam chest of the first effect is annular in shape, the outside diameter being 9 inches and the diameter of downcomer 3-3/4 inches. The overall length of the chest is 18 inches and there are 32 3/4-inch x 16 gauge heating tubes. Steam is admitted to the mid-point of the outside shell and condensate withdrawn from the bottom. (Figure 5). A small reservior is mounted in the 1/2-inch condensate line in which the level is controlled to prevent the loss of live steam.

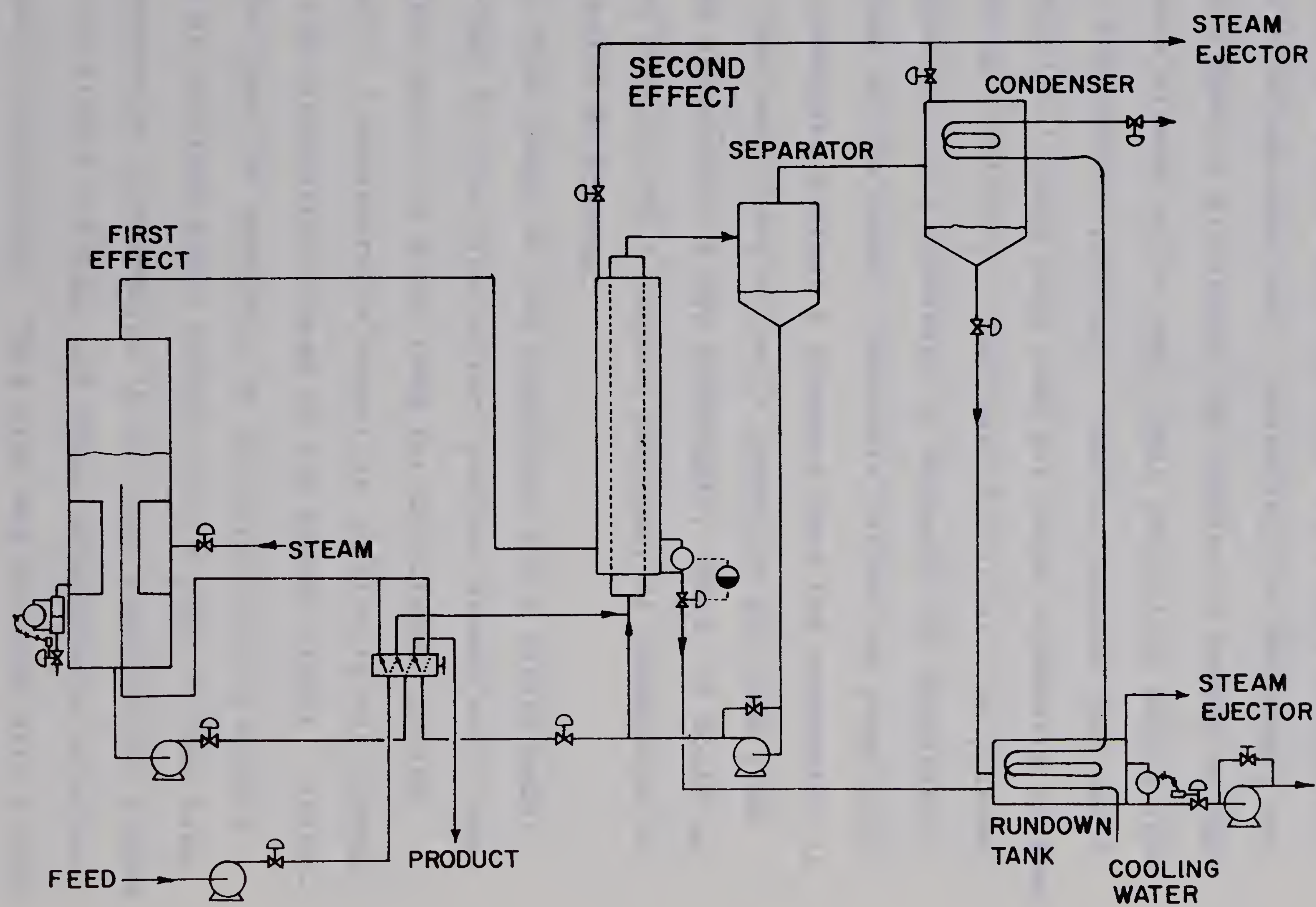
Three 1-inch x 16 gauge tubes, 6 feet in length, constitute the heating surface of the second effect. Condensate in this effect is withdrawn through a hole bored in through the side of the 10-inch diameter bottom plate into which the 3 heating tubes are welded. Vapor loss is prevented by maintaining a level of condensate in the bottom of the vapor space around the tubes. The pressure taps for the liquid level transmitter enter, one through the side of the bottom plate and the other through the glass tee at the steam inlet. (Figure 4) The heating tubes are sealed in the 10-inch diameter top plate by O-rings to allow for the difference in thermal expansion of the stainless steel heating tubes and outer glass wall to which

the plates are clamped. Vapor is admitted to the bottom part of the second effect so as to allow the removal of accumulated air without much loss of live vapor. The current of vapor up the steam cavity before condensing on the tubes creates a fountain effect which causes the air to accumulate at the top from where it is bled through a hole in the side of the top plate. The method used to prevent loss of live vapor through the bleed line will be explained later in this chapter. Were the vapor to enter the top of the steam cavity the air would accumulate at the bottom but its removal would be complicated by the presence of condensate.

One unique feature in the design of this evaporator is the use of a multi-valve for switching from forward-feed to reverse-feed operation. A schematic diagram of the valve's operation can be seen in Figure 5. The inputs to this valve are the three solution streams, that is, feed, product from the first effect and product from the second. At one end of its stroke the valve directs the streams for forward-feed operation while at the other end for reverse-feed. The controls of the evaporator are also organized so that the mode of operation can be reversed by merely flipping a switch.

It can be seen in Figure 5 that the condensate lines from the second effect and final condenser run into a run-down tank which has cooling coils in it. The potential for flow of these two streams into the tank was provided by connecting the

FIGURE 5 SIMPLIFIED SCHEMATIC OF THE EVAPORATOR PIPING



steam ejector, used to create the vacuum for this evaporator, directly to this run-down tank. Arranging the condensate removal in this fashion eliminates the problem of having to pump two condensate streams at or near their saturation points from a vacuum to atmospheric pressure. Another problem that would occur if individual pumps were used for these condensate streams is the start up difficulty. For reasons that will be pointed out in Chapter VI it is necessary to evacuate the evaporator before turning on the steam. Therefore, since the pumps will not prime themselves against a pressure once the evaporator is evacuated, they would have to be in operation for some time prior to the production of any condensate. Thus, it would be necessary to have or add a certain inventory of condensate to the system prior to startup.

Two other pumps on the evaporator are a Viking model 5H54F gear-pump for the first effect product stream and a Robbins and Myers model 1L4 Moyno pump for circulation in the second effect. A considerable amount of difficulty was encountered with the circulation stream of the second effect. Initially the line from the separator to the circulation pump was constructed of 1/2-inch pipe, however, for a pipe of this size any vapor bubbles or air bubbles in the line retarded the liquid flow enough to starve the pump and cause considerable noise and vibration due to cavitation. This line was replaced with 1-inch tubing, but even then cavitation sometimes occurred. The final

piping configuration used consisted of a 2-1/2-inch pipe mounted vertically on the pump and extending up to a point above the liquid level of the separator with a 1-1/2-inch pipe extending from the separator into the side of the stand-pipe. The heat of liquid in the cyclone is enough to drive the solution into the stand-pipe through the 1-1/2-inch line and any vapor or uncondensibles in the stand-pipe can rise without impeding the flow and escape through the top of the stand-pipe which is connected to the vapor space of the separator by a 1/4-inch line.

Two other pumps used in the evaporator operation are both Fostoria Corporation model 882E dynapumps. One is used for general materials movement in preparing feed, etc. and the other is the feed pump.

Feed is stored in two 200-gallon glass-lined hot water tanks, the product in a 140-gallon tank and the condensate in another 200-gallon glass-lined tank. A piping system was constructed so that, with the pump provided, various operations such as filling, draining and mixing of individual tanks or the blending of new feed from the product and condensate could be performed. This necessitated the use of some fifteen valves, so for convenience, solenoid valves were used. To perform any one pumping operation on the tanks a certain combination of valves must be on and/or off, but because of the number, there was some concern about the possibility of an error causing the ruin of an

experiment. As a safeguard against this possibility, a solenoid switching arrangement was designed which prevents the performance of any pumping operation that might ruin an experiment while the evaporator is in operation. Details are given in Appendix 2.

Figure 6 is a diagram of the angle-iron framework used to hold the evaporator. The framework was bolted to the floor and braced so as to minimize vibrations. Figures 7, 8 and 9 are photographs of the evaporator as it appears ready for operation.

B. Control

As mentioned in Chapter I, a necessary prerequisite for the quantitative study of the control of a process is a model describing the transient behavior. However, since the aim of this work is to develop and test such a model there was none available at the time the control scheme was being designed and thus the study of various control schemes consisted mainly of qualitative considerations based upon engineering intuition. Designing the control scheme in this manner resulted in the control configuration being altered, on the process, four times before establishing a configuration that worked satisfactorily.

In the majority of continuous separation processes the ultimate aim of controls on the process are to maintain the product at a certain composition. For evaporators the most common

requirement. As a safeguard against this possibility, a suitable switching arrangement was designed which prevented the perfor- mance of any pumping operation that might lead to contamination while the thermostat is in operation. Details are given in Appendix B.

Figure 8 is a diagram of the analytical equipment used to hold the thermostat. The thermostat was bolted to the floor and mounted so as to minimize vibrations. Figures 7, 8 and 9 are photographs of the apparatus as it appeared ready for opera- tion.

4. Control

As mentioned in Chapter I, a necessary prerequisite for the quantitative study of the control of a process is a model describing the transient behaviour. However, since the aim of this work is to develop and test such a model there was none available at the time the control scheme was being designed and thus the study of various control schemes consisted mainly of qualitative considerations based upon engineering intuition. Designing the control scheme in this manner resulted in many detailed modifications being effected on the process; four times before establishing a configuration that worked satisfactorily.

In the majority of continuous separation processes the ultimate aim of control in the process is to maintain the pro- duct at a uniform composition. For evaporators the most common

FIGURE 6 EVAPORATOR FRAMEWORK

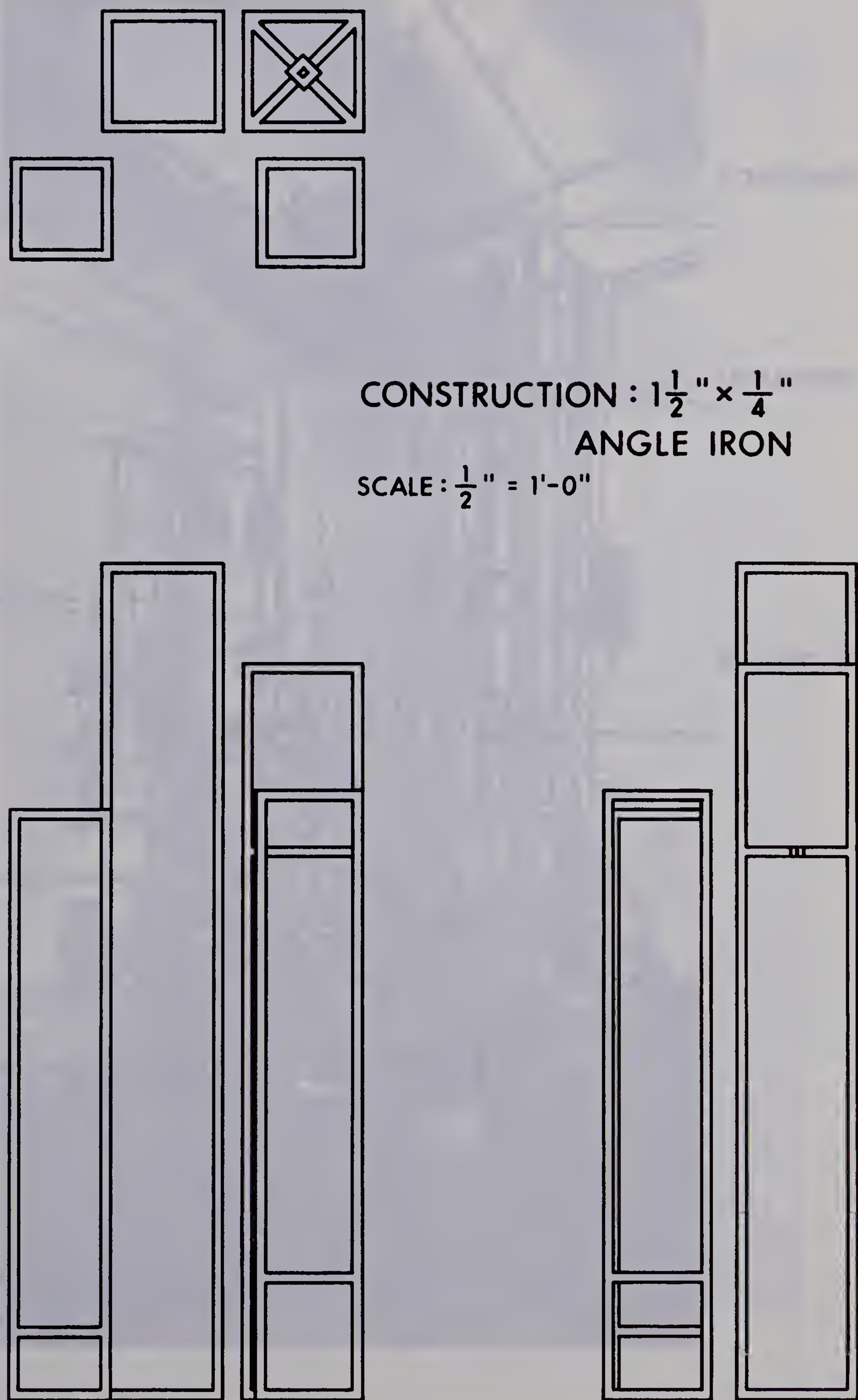


FIGURE 7 EVAPORATOR

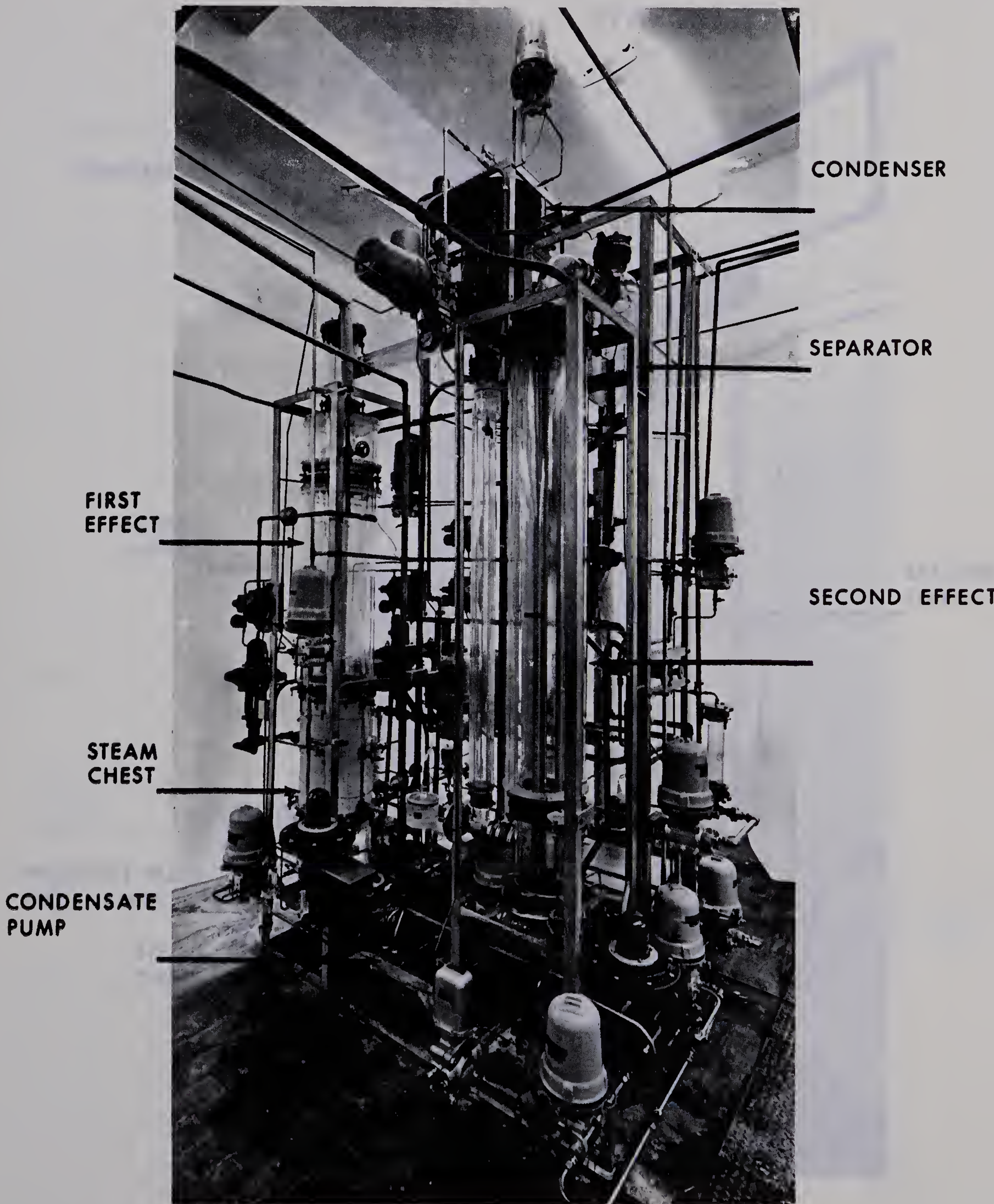


FIGURE 8 EVAPORATOR

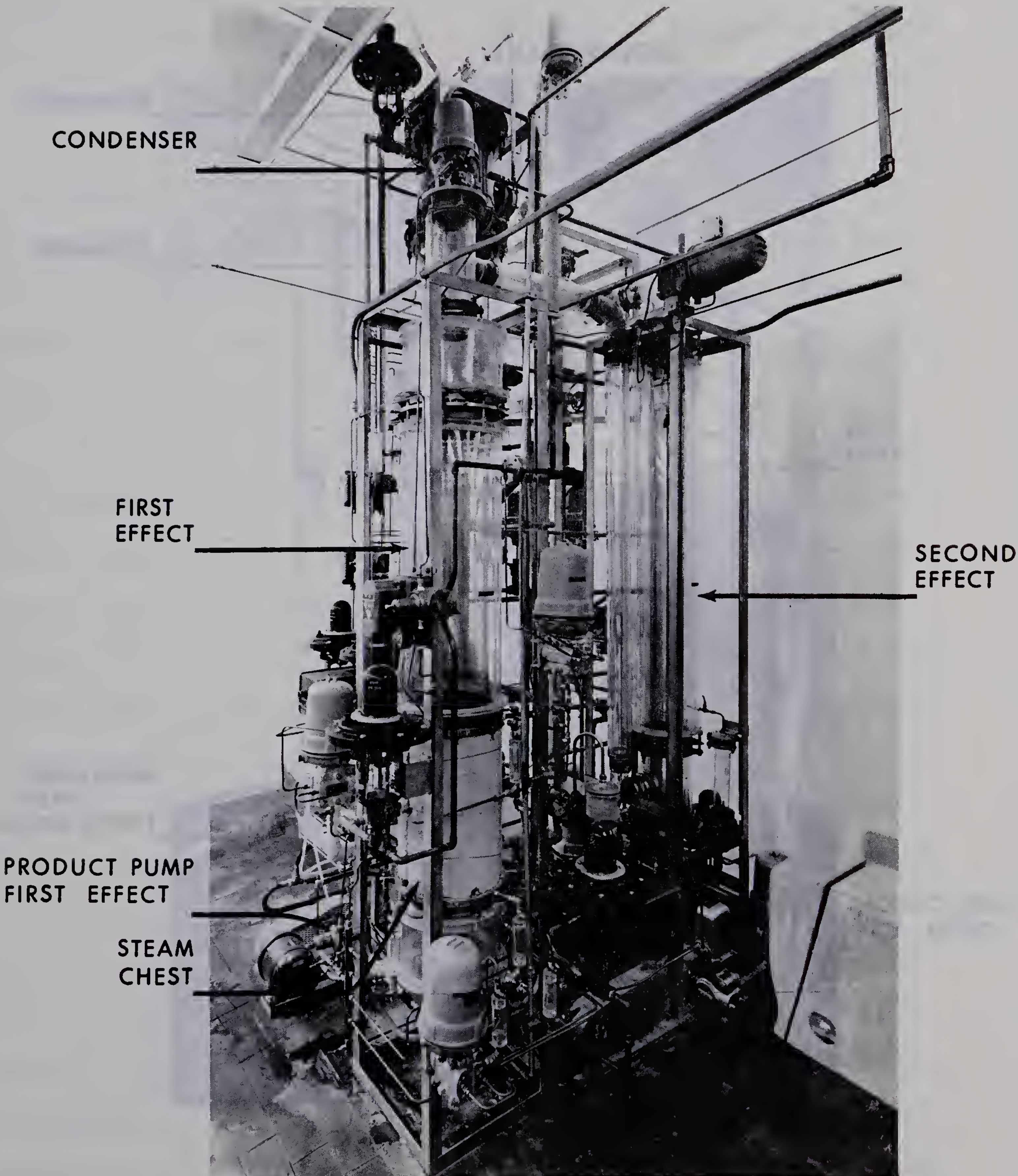
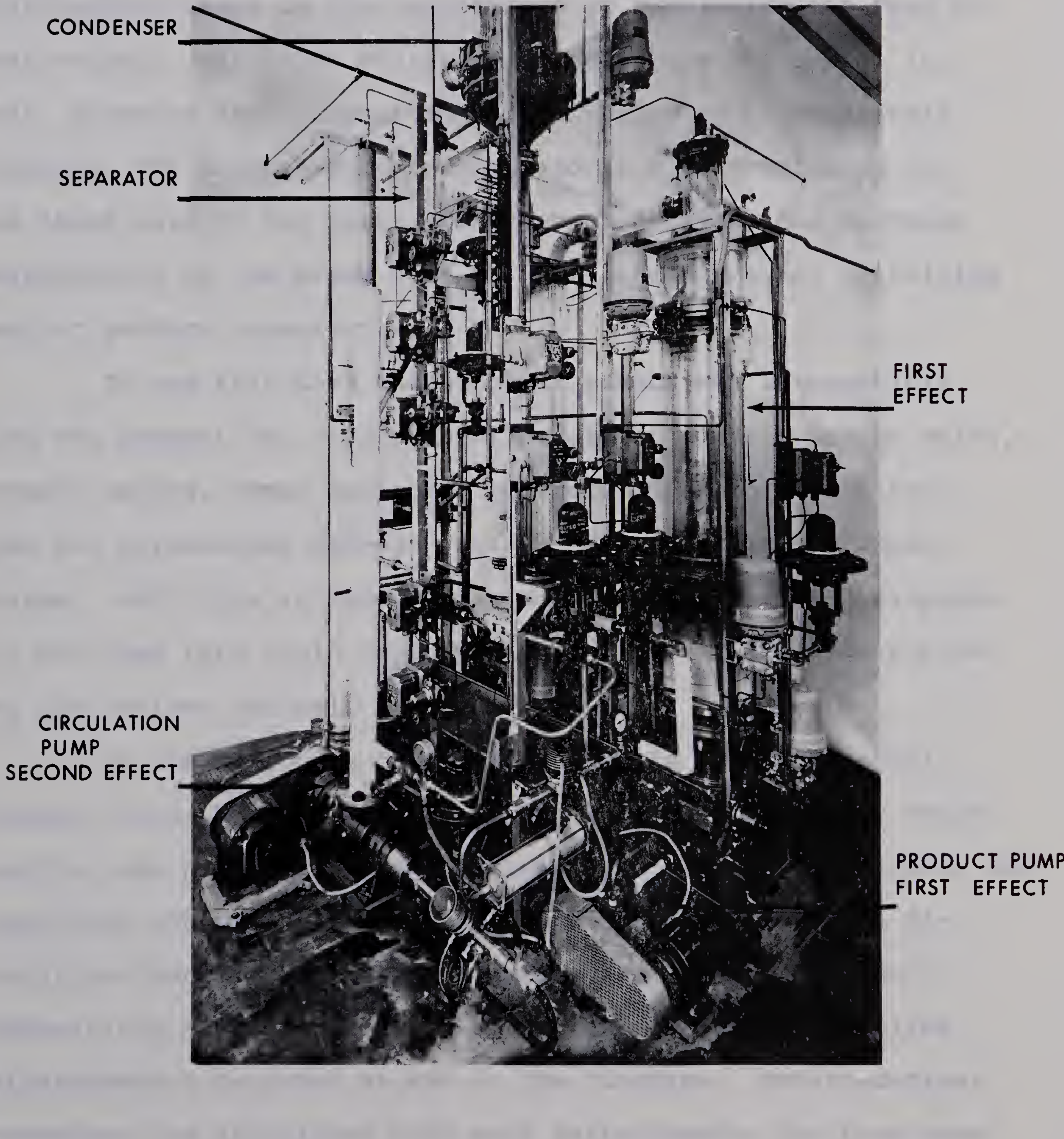


FIGURE 9 EVAPORATOR



way of achieving this goal(24) is to regulate the product stream, throttling back for enrichment. The level in each effect of a multi-effect chain is then maintained by regulating the feed to that effect. The major criticism of this type of control is that, assuming feed composition and enthalpy to be relatively constant, the through-put of the evaporator is determined by the steam rate to the first effect which necessitates operator manipulation of the steam rate to take care of rising or falling feed or product inventory.

It was felt that this control scheme was incompatible with the present day "system" philosophy of control design which, crudely stated, means designing controls so as to remove the need for inventories between various operations in a process system. With this in mind it was decided that for this evaporator the feed rate would be unavailable as a variable for achieving the desired control.

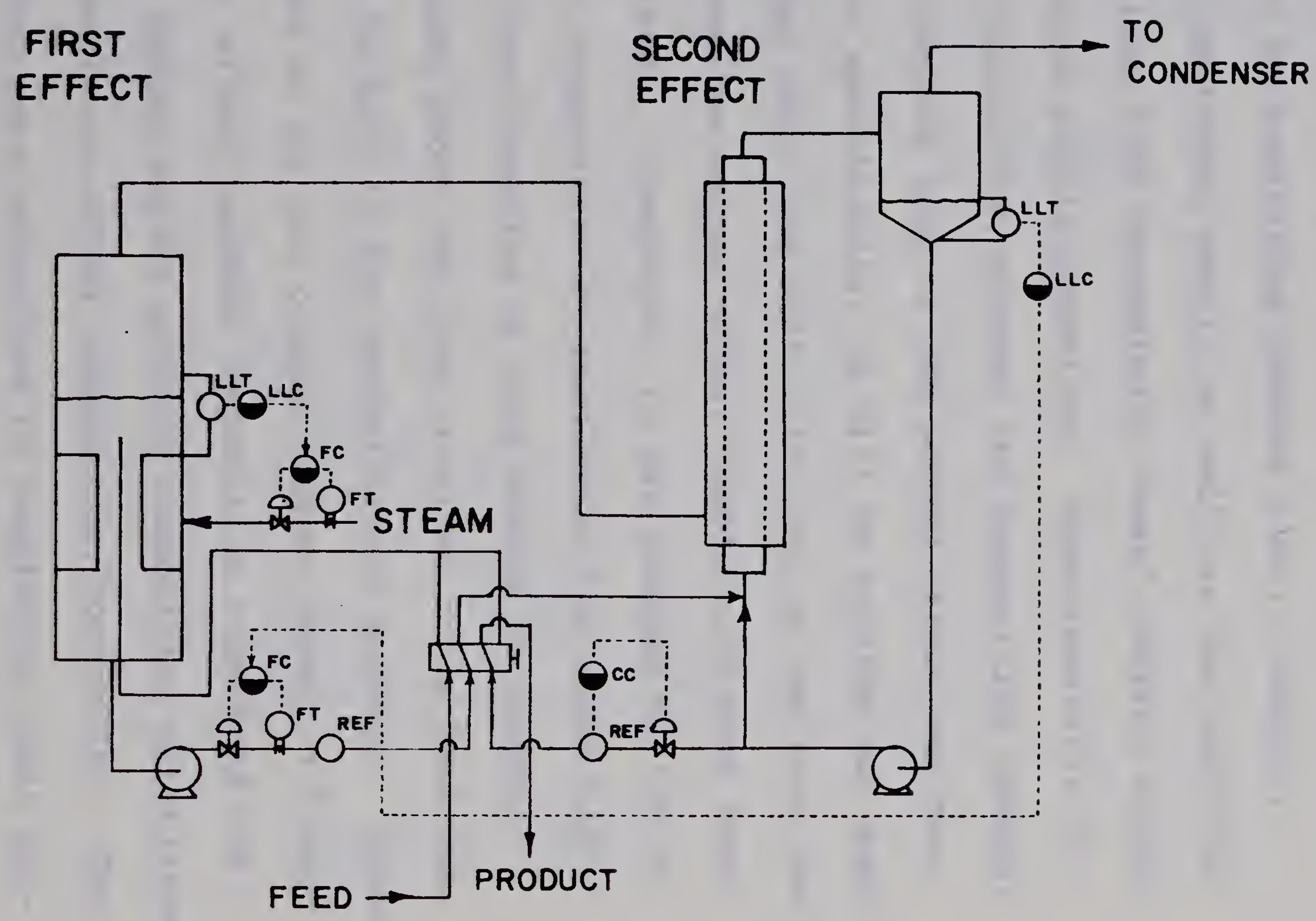
In the following descriptions of the various control schemes tried, Figures 10, 11, 12 and 13 are referred to, which require some preliminary explanation. The first three figures are simplified schematic diagrams in which those controls not directly influencing the system dynamics are omitted. Product compositions are measured with Waters and Associates Monoline Refractometers depicted as REF in the diagrams. EMF-to-current converters are associated with each refractometer but have been omitted from the first three diagrams for clarity. A complete

legend for all the control diagrams is given in Appendix 1.

The initial control scheme selected is that shown in Figure 10. Product composition was controlled by regulating the product rate. The level in the second effect was controlled by regulating its feed stream, which is the product from the first effect and the level in the first effect was controlled by regulating the steam rate. This control scheme, however, proved to be unsatisfactory since stable operation could not be achieved. The problem lay in the fact that the first effect level is less sensitive to steam changes than are the downstream variables. For instance, in the course of experimenting with this control scheme it was noticed that the steam rate had a greater influence on the second effect level than on the level of the first effect even though the x-sectional areas of both effects are equal and the latent heats of evaporation are approximately equal. Though this result caused some consternation initially, it can be explained by considering the result of say a step up in steam rate. The solution temperature as well as the vaporization rate will rise and thus since the temperature of the second effect is constant, the vaporization rate of the second effect rises enough to compensate for both the increased heat transfer from the first effect vapor and the warmer feed. There is also a reduced quantity of liquid feed to the second effect.

For this reason it was decided to rearrange the controls

FIGURE 10 SIMPLIFIED SCHEMATIC OF THE FIRST CONTROL SCHEME



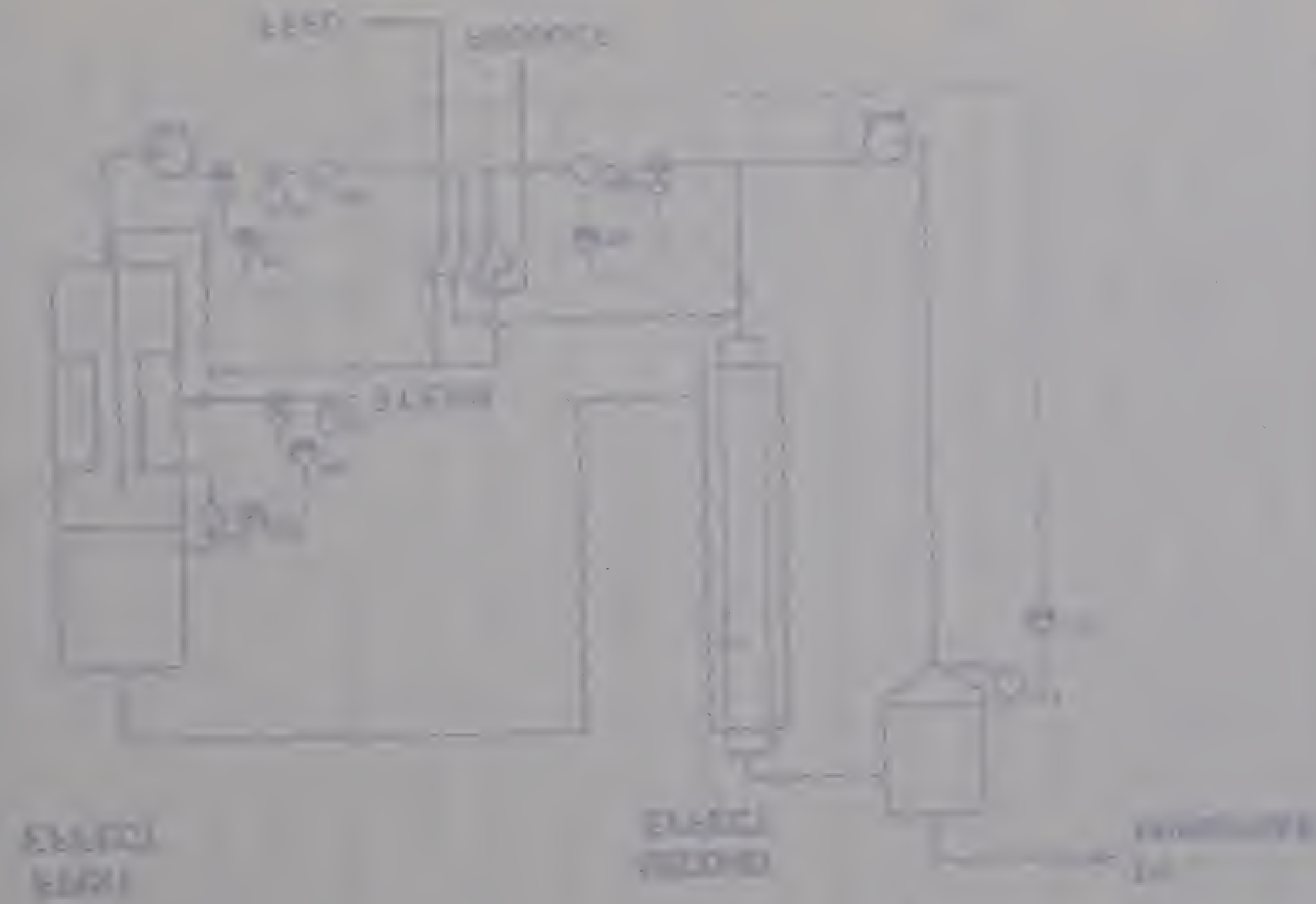


FIGURE 10 SIMPLIFIED SCHEMATIC OF THE FIRST CONTROL SCHEME

to that shown in Figure 11, where the level in the first effect was controlled by regulating its product and the second effect level controlled by regulating the steam. Product composition was still controlled by regulating product flow. However, this control scheme performed nearly as badly as the previous one, giving indications that exceedingly "weak" control action was required to achieve stable operation. Experimentally it appeared as though interaction between the composition control loop and the level control loop of the second effect was the chief problem. More specifically, as will be pointed out quantitatively in Chapter VIII, the difficulty lay in the fact that steam rate influences the second effect composition more than the second effect level. Therefore, it was decided to try to control the product composition by regulating the steam flow.

During the consideration of this method of control there was some concern about the lags involved for a feed composition change to be felt in the second effect product. Therefore, it was decided to try the control scheme shown in Figure 12, where the first effect product composition regulated the steam rate and the second effect product composition established the set-point of the first effect composition controller. The levels in each effect were controlled by regulating their product streams.

This control scheme, however, performed no better than the first two. Attempts to find the right combination of con-

FIGURE II SIMPLIFIED SCHEMATIC OF THE SECOND CONTROL SCHEME

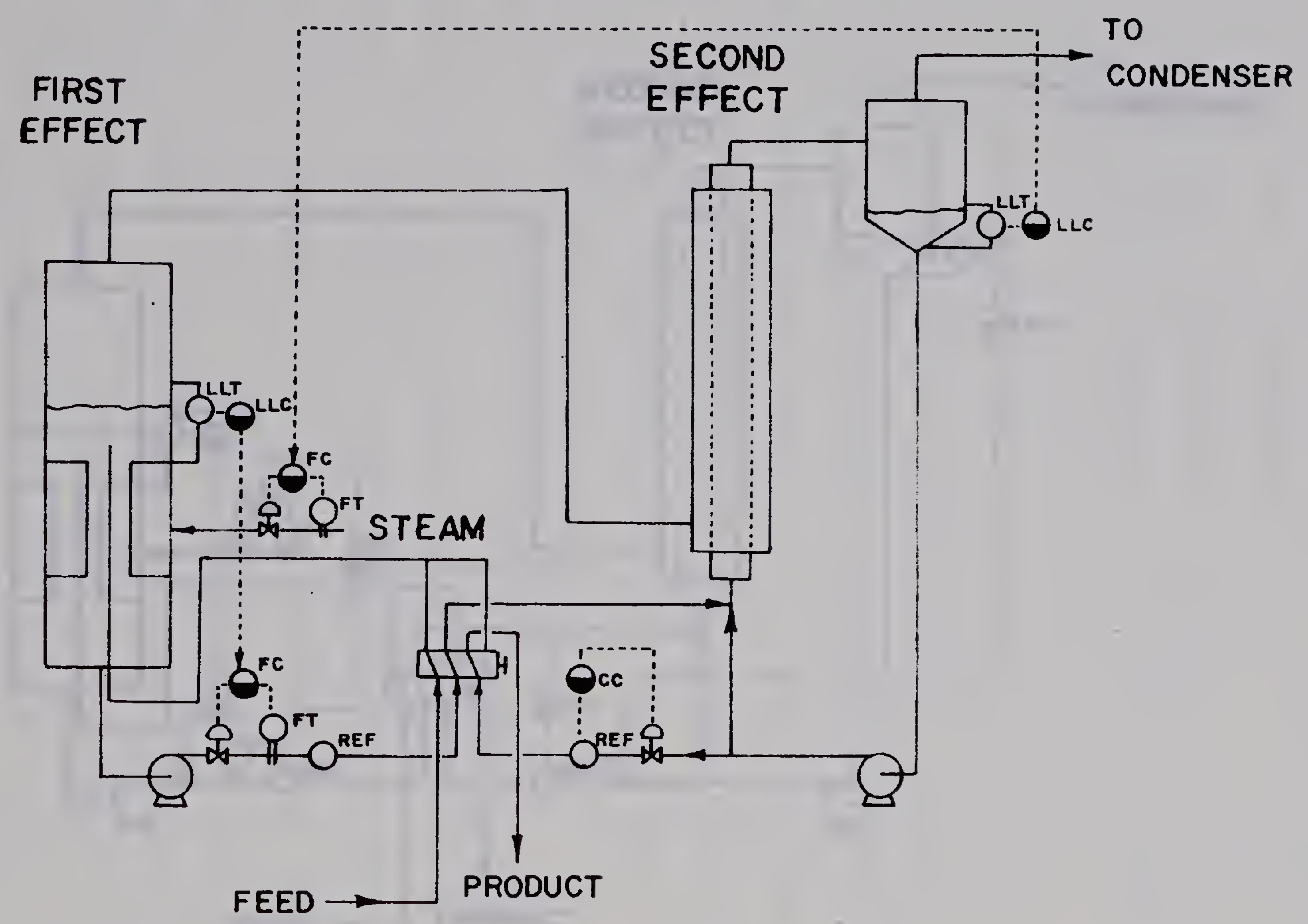
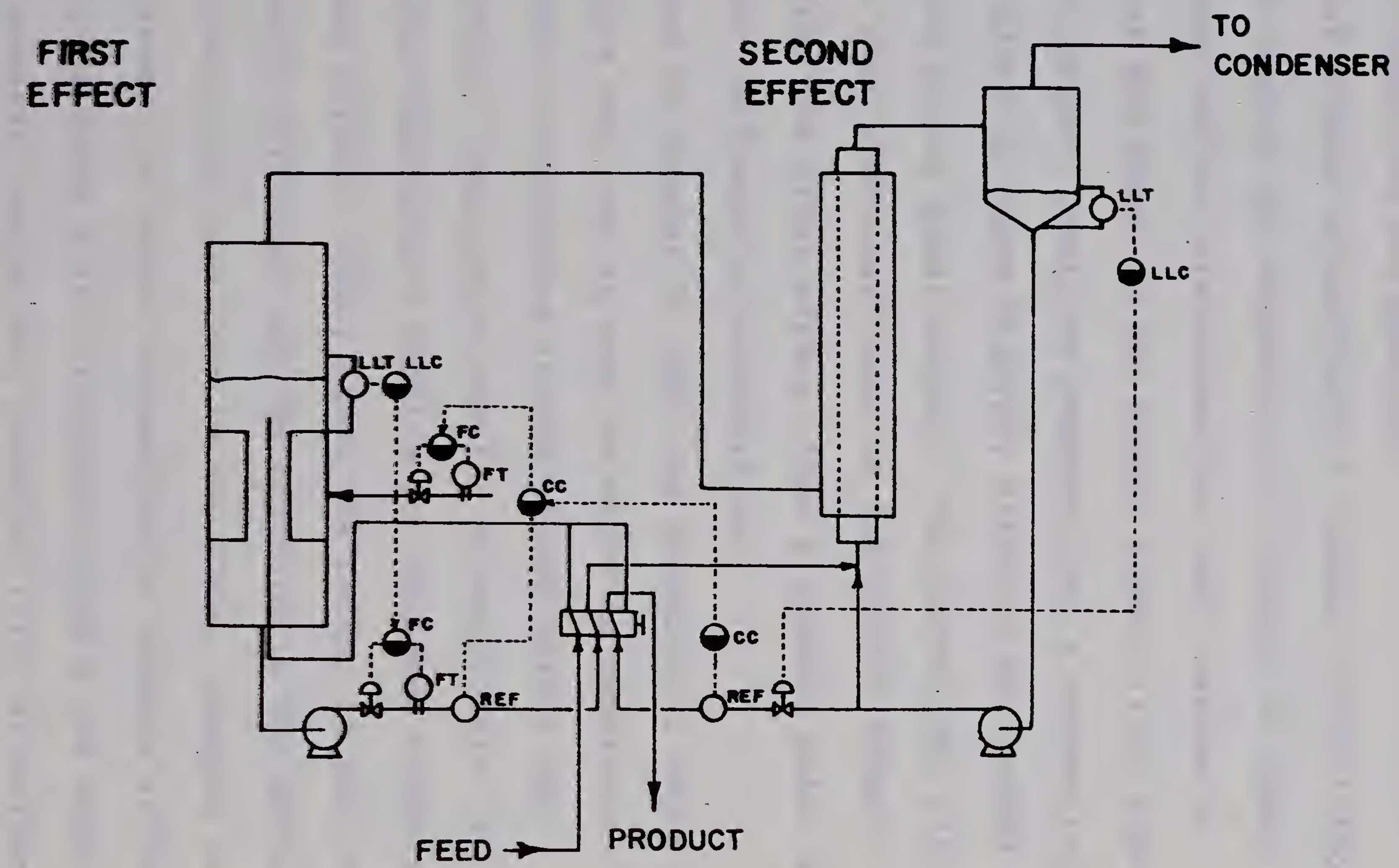


FIGURE 12 SIMPLIFIED SCHEMATIC OF THE THIRD CONTROL SCHEME



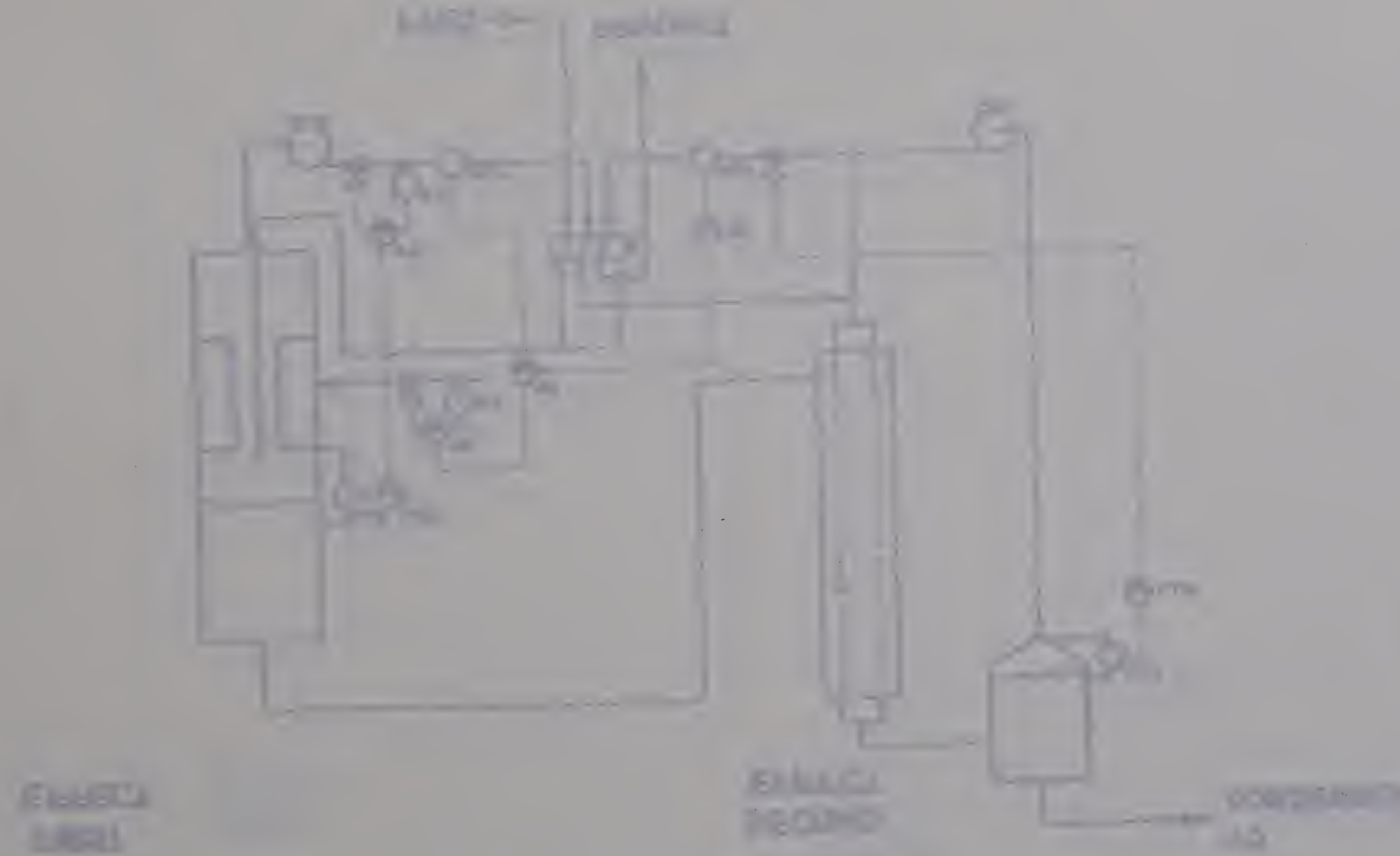


FIGURE 6 SIMPLIFIED SCHEMATIC OF THE THIRD CONTROL SCHEME

troller settings for the two concentration controllers proved to be fruitless. The reason for this difficulty became apparent once the model was completed and analyzed.

This control scheme is basically a cascade control loop which is especially suited for correcting for supply or input changes. The thought behind this scheme was that changes in the concentration of the input to the second effect (i.e. product from the first effect) would be measured and a correcting action undertaken prior to these changes, altering the second effect concentration to any great amount. The factor not initially realized is that the other input to the second effect, namely the vapor from the first effect, from a dynamic point of view,has the greater influence on composition.

It was shown in Chapter IV that the dynamics of vapor holdup are negligible and thus as soon as vapor is generated from the first effect it condenses in the second effect and since the second effect temperature remains constant this increased heat transfer immediately results in increased vaporization from the second effect. Also, since the holdup in the two effects is not greatly different and the solution in the second effect is more concentrated than that in the first, changes in vaporization rate result in larger concentration changes in the second effect (i.e. Removing 1 lb. of solvent from a 10% solution results in a greater change than removing 1 lb. of solvent from a similar amount of 5% solution.)

[illegible] for the [illegible] [illegible] to the [illegible]. The reason [illegible] since the model was completed and analyzed.

This [illegible] is especially suited for [illegible] the supply of [illegible]. The [illegible] the compensation of the [illegible] from the first [illegible] would be [illegible] and a [illegible] prior to [illegible] without [illegible] of any [illegible]. The [illegible] is that [illegible] of the second [illegible] namely the [illegible] from the [illegible] from a [illegible] which is [illegible] the greater [illegible] on [illegible].

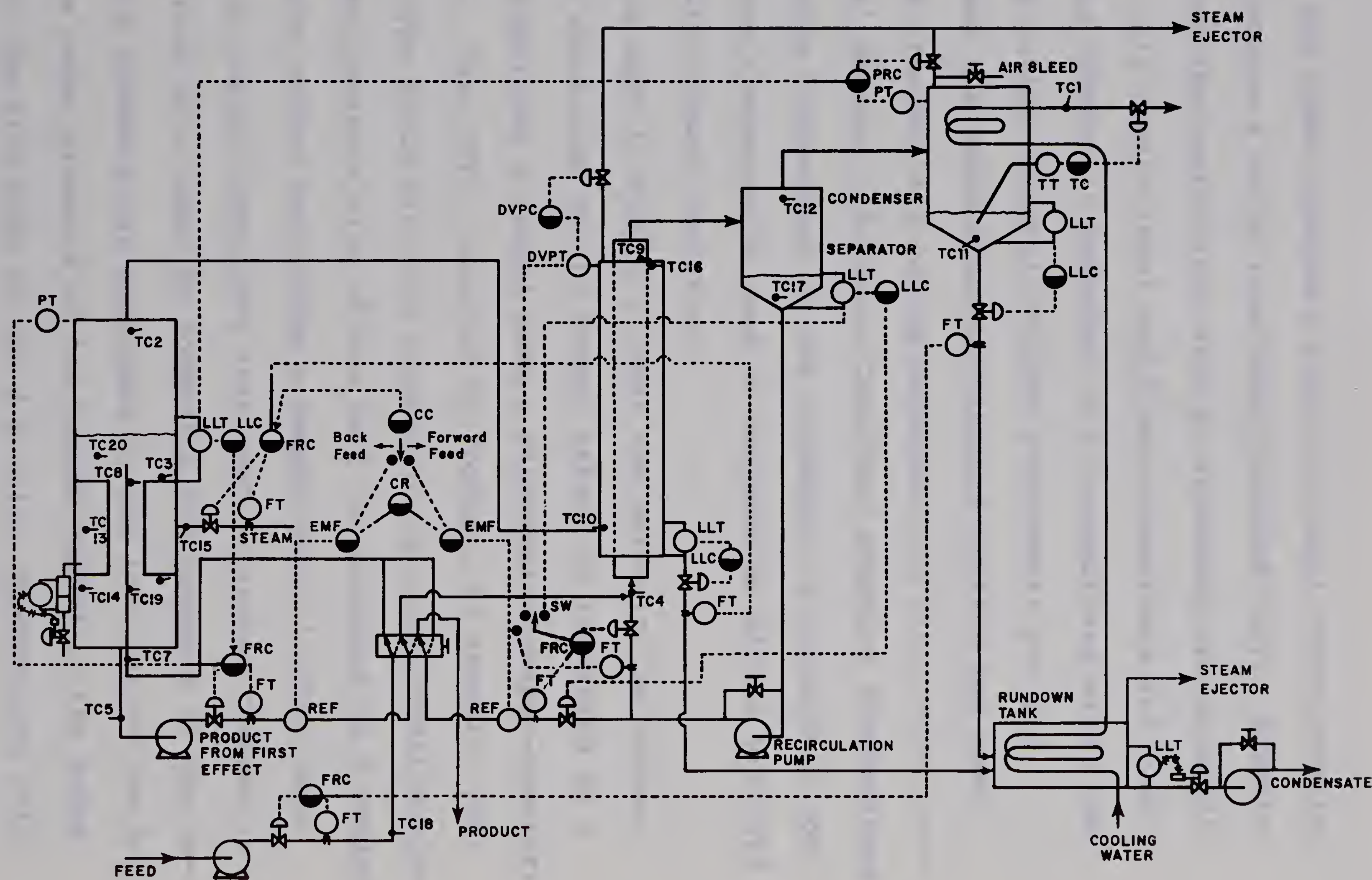
It was shown in Chapter [illegible] that the [illegible] of [illegible] from the first [illegible] to the second [illegible] from the second [illegible] from the second [illegible]. [illegible] of the second [illegible] in the [illegible] of a [illegible].

Thus, the pertinent result is that a steam flow change alters the second effect concentration almost as quickly but to a greater degree than it alters the first effect concentration and since the inner control loop required a fairly large proportional band for stability the net result of this cascaded control is to add another lag to the control loop.

Therefore, the control scheme was altered to that shown in Figure 13 where the second effect product composition is controlled by regulating the steam to the first effect and the level of each effect controlled by regulating the product flow rates. Utilizing this scheme satisfactory control of the evaporator was achieved, the evaporator returning to steady state within approximately three hours when tested with a variety of input disturbances. An additional benefit that arises from this control scheme is that to switch from forward to backward feed the input to the composition controller is changed from the composition transmitter (i.e. Refractometer-EMF converter combination) of the second effect to that of the first effect, the two level controllers remaining unchanged. For the previous control schemes the switching arrangement would be much more complicated.

Also shown in Figure 13 are all the auxiliary controls and monitoring equipment associated with the evaporator. All the controllers indicated in Figure 13 are Foxboro Electronic Consotrol controllers. The controllers indicated as recording

FIGURE 13 EVAPORATOR AND CONTROLS



controllers are 2-pen recorders with the signal shown entering the controllers as a solid line being recorded only. Signals shown entering the controllers with an arrowhead are external set points. All liquid level and flow transmitters are type 613DM Foxboro Electronic Consotrol d/p transmitters with flow transmitters having integral orifice attachments for all streams except the steam where an external orifice was used. The pressure transmitters on the condenser and first effect are both type 611 Foxboro Electronic Consotrol pressure transmitters. The temperature transmitter on the condenser is actually a copper-constantan thermocouple used in conjunction with a type 693 Foxboro EMF-to-current converter.

It is seen in Figure 13 that the valve in the vacuum line to the steam side of the second effect is regulated by a controller receiving a signal from a differential-vapor-pressure transmitter. This DVPT, supplied by Foxboro, is actually just a standard type 613DM d/p cell transmitter with the modification that the high pressure side of the cell is connected to a sealed vapor pressure system containing a sample which in this case is water. In normal operations this DVPT indicates changes in the composition of a vapor by comparing the pressure of the vapor through a pressure tap connected to the low side of the d/p cell, to the vapor pressure of the sample sealed in the probe connected to the high side of the d/p cell. However, on this evaporator the DVPT acts more as a differential temperature

transmitter. As was mentioned in the early part of this chapter the current of vapor in the second effect tends to cause any air coming into the system (i.e. dissolved in the feed) to accumulate at the top of the steam chest. This stratification results in the air layer having a pressure equal to that of the vapor. Thus in principle a DVPT would not work as a composition detector. However, as the probe was located at the top of the steam chest it detected the presence of air by virtue of the air's lower temperature. Operating in this fashion the DVPT and associated controller prevented the accumulation of air in the second effect steam chest without much loss of vapor.

The flow control loop in the circulation stream of the second effect was put there to insure a day to day continuity in the liquid velocity and thus heat transfer coefficient in the heating tubes of the second effect. As it turned out, this flow control loop also contributed to a smoother evaporator operation since when the controller was put on manual control and, the valve opened full, there appeared to be bumping or oscillation in the second effect heat transfer coefficient evidencing itself as fluctuations in the pressure of the first effect. The control valve was operated near full open so as not to lose too much pump capacity. The switch (sw) shown in the input to the recording flow controller of this loop was placed there so that one pen might be used for recording either the level in the separator, the circulation flow or the output of

the DVPT, since neither of the latter two signals is required for transient analysis, but may be required for steady state analysis or at startup. The other pen of this recorder-controller permanently records the second effect product rate.

Temperatures at various locations through the evaporator were measured by the thermocouples indicated in Figure 13. The shielded copper-constantan thermocouples were supplied by Thermo Electric. A Honeywell type 153 Electronik Multipoint recorder was used to record the thermocouple signals.

The only remaining control operations on the evaporator requiring explanation are the liquid level control of the rundown tank and reservoir in the condensate line of the first effect. In both of these cases the signal from the liquid level transmitter goes directly to a valve positioner which acts as a proportional controller. The control was excellent in both cases.

Instruments depicted in Figure 13 with a darkened lower hemisphere are mounted on a panel board, the others being mounted on the process. A picture of the panel board is shown in Figure 14.

C. Operation

Though the operation of the evaporator is quite satisfactory, the startup procedure is somewhat more complicated

FIGURE 14 CONTROL PANEL

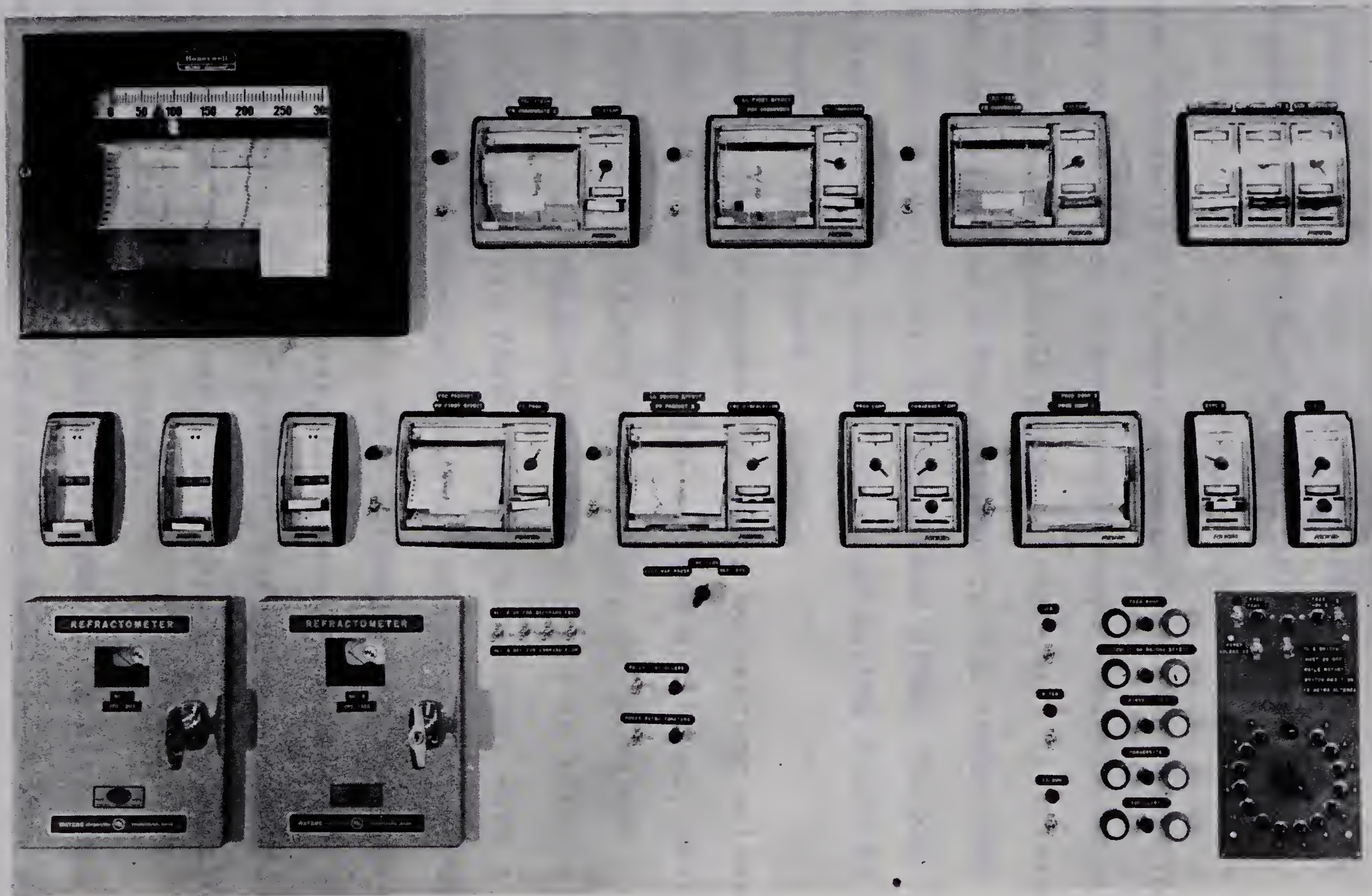


FIGURE 14 CONTROL PANEL

than might be desired for an undergraduate unit operations experiment. However, it is felt this is more a result of the nature of the process rather than a fault of this particular evaporator.

Because the system is under a vacuum while in operation it is necessary to fill each effect with enough solution to allow the bleeding of all d/p cells prior to start up. Also since the system must be evacuated before turning on the steam, the product pumps must be operating, in the second effect to prevent air from backing up the product line and in the first to maintain the second effect level.

This requirement of evacuation prior to heating arises from the fact that with the condensing surface air bound, heat input merely increases the liquid temperature, and when the vapor finally reaches the condensing surface there is a rapid drop in pressure causing high flash evaporation rates, with a good deal of splashing. Because a perfect vacuum could not be drawn, this splashing did result, to a degree, in this evaporator. Consequently, it is necessary that levels not be too high at the onset of boiling so as to prevent loss of solution from splashing. Because of the separator size this was more critical in the second effect than in the first.

The above-mentioned difficulties made it necessary to start the evaporator with the liquid levels manually controlled. As soon as boiling started they could be switched to automatic control.

With the controller settings used in this work it was not possible to start with the composition controller regulating the steam. The procedure used was to manually set the steam rate approximately 20% higher than normal until the concentration was within 10% of its set point and then to return the steam rate to normal and set the composition controller onto automatic.

Using the above-mentioned procedures it took approximately six hours for the evaporator to reach steady state after startup. As previously mentioned, once having reached steady state it took approximately three hours to regain steady conditions after a deliberately imposed upset.

With the exception of the refractometers, the instrumentation performed in a trouble-free manner. The performance of the refractometers, however, left much to be desired. The problem unfortunately lay in the basic design of both the measuring head and amplifier and thus correcting for it would have entailed a complete remodelling. However, after no small amount of effort, a stage was reached where the refractometers could be depended upon for at least the course of an experiment, but this entailed calibrating the refractometers for every experiment.

The only other aspect of the evaporator's operation that caused major concern resulted from the type of pump used for the feed. The Fostoria Dynapump provides for cooling of

its motor by allowing the pumped solution to circulate around the armature which,of course, results in heating of the solution. Since a part of the feed pump output is returned to the feed tank for mixing purposes, the result is a gradual rise in the feed temperature. A small heat exchanger was placed in the feed line, with the cooling water being manually controlled. This eased but did not completely eliminate this problem.

VI. EXPERIMENTAL PROGRAM

The major purpose of the experimental program performed on this evaporator was to acquire enough data to check the validity of the theoretical model. For chemical engineering processes the three most common methods of achieving this end are frequency testing, pulse testing and transient testing.

Of these three methods probably the most comprehensive is the first or frequency testing method. However, from an experimental point of view it is also the most difficult. As was mentioned in Chapter III, the primary difficulty lies in the experiments at both ends of the range of frequencies used. For high frequencies the response often is buried due to noise and at low frequencies the problem lies in keeping other parameters steady for the duration of the run. Furthermore, since the testing program will take several weeks to complete, there is the problem of duplicating experimental conditions from day to day.

A second major criticism of this method of model evaluation is that strictly speaking it is applicable only to linear systems. Of course, the model could be linearized and the results of frequency testing compared to that predicted by the linear model, but this then adds a third parameter to the final analysis. That is, besides experimental error and/or basic model inaccuracies, disparities between predicted and actual responses could also be partially attributed to the

errors inherent is using linear equations to describe a non-linear system. Because of these reasons, especially the experimental difficulty, it was decided that frequency testing would not be undertaken for model verification.

The pulse-testing method(11) provides a means whereby the same data that are obtained from frequency-testing, namely amplitude ratios and phase angles, can be obtained for all frequencies from the results of one test. These data are achieved by operating on the experimental data in the following fashion. Let X be the stream or parameter being measured and Y the parameter being pulsed. If G is the transfer function relating the two, then in Laplace transform notation

$$G(s) = \frac{X(s)}{Y(s)}$$

which can be written as

$$G(s) = \frac{\int_0^\infty e^{-st} X(t)\, dt}{\int_0^\infty e^{-st} Y(t)\, dt}$$

Substituting $i\omega$ for s and further substituting $\cos(\omega t) - i \sin(\omega t)$ for $e^{-i\omega t}$ yields

$$G(i\omega) = \frac{\int_0^\infty \cos(\omega t)\, X(t) dt - i \int_0^\infty \sin(\omega t)\, X(t) dt}{\int_0^\infty \cos(\omega t)\, Y(t) dt - i \int_0^\infty \sin(\omega t)\, Y(t) dt}$$

Thus, evaluating the above integrals for all the frequencies of interest, the amplitude ratios and phase angles of $G(i\omega)$ can be obtained. The fact that these data can be obtained from the results of one test makes this method much more appealing than direct frequency-testing. Moreover, on the basis of results published in the literature(11, 12, 17) it would appear that the accuracy of pulse-testing compares favorably to frequency-testing.

It can be seen that as with frequency-testing, pulse-testing is limited to linear systems and for this reason direct transient-testing rather than pulse or frequency-testing was used to verify the model in this work. It is acknowledged that in situations where a model is being derived on the basis of experimental data, frequency data is to be preferred to transient data but in situations where a model has been derived from physical considerations the pulse-testing method provides no benefits over transient-testing.

The standard method of transient testing is to apply a step to the pertinent input parameter and to check whether the predicted and actual responses agree. However, there is no reason why the disturbance applied could not be a pulse rather than a step. If the predicted and actual responses for a pulse input did not agree then it is felt that neither would the frequency data.

In the course of these experiments on the evaporator,

the most serious problem encountered was the previously mentioned difficulty with the concentration measuring refractometers. Because they could not be relied upon to hold their calibration it was necessary to take samples while the evaporator was going through an induced transient. Samples (20 cc each) were taken at 10 minute intervals and in comparison to a holdup of approximately 30 lbs. per effect and a throughput of approximately 3 lbs./min. it was felt their effect upon the system was negligible. These samples were analyzed on a Bellingham and Stanley refractometer. Using this instrument, concentrations of the samples were determined to within .01 weight percent.

Another problem of major concern was an apparent change in the calibrations of the two product flow transmitters from day to day. For the second effect or final product stream this problem was easily overcome since the product stream could be continually calibrated while the evaporator was in operation. However, the first effect product stream could not be calibrated without shutting down the evaporator. It was felt that this calibration change might have been caused by a deposition of sugar crystals in the d/p cells as the process cooled after shut down, since sugar deposits made it necessary to dismantle and clean the second effect product valve on two occasions to restore smooth operation to the valve.

Recognizing that continuous operation would alleviate this problem and further that most process equipment prefer continuous to intermittent operation, it was decided to perform all experiments while operating the evaporator for extended periods. Thus, all the experiments were conducted during the course of one two-day and two week-long runs.

Another major problem connected with the experimentation was that of noisy records. The two liquid level transmitters were the most troublesome in this regard; the first effect due to the boiling action and the second effect due to surging (of unknown cause) in the circulating stream entering the separator. This noise unfortunately carried through to the respective flow steams regulated by these liquid levels. The flow transmitter in the first effect product stream had another obvious source of noise, namely vaporization of the saturated solution (at the first effect pressure) as its pressure dropped in passing through the valve and flow transmitter orifice. The frequency of a major portion of this noise was roughly between .3 and .5 cps and thus could not easily be damped electronically. Therefore, in order to make the records more readable mechanical pen-arm dampers were purchased which reduced the noise band width to a considerable degree.

Because of the experimental difficulties mentioned above, only 6 experiments were obtained which are suitable

for use in comparing experimental and predicted transient responses. However, it is felt that these experiments are sufficiently diverse in their operating conditions and input disturbances to provide an adequate test for the model. Three of the experiments are for closed loop operation (i.e. product composition regulating steam flow) and 3 are for open-loop operation (i.e. steam rate manually set). The nature of these experiments is given in Table 1-A. An indication of the range of conditions covered by these experiments can be seen in Table 1-B which lists the maximum and minimum values attained by some of the pertinent parameters of the system.

For all of these experiments the feed composition was kept near 3% and save for changing this concentration, the evaporator could not be operated much beyond the indicated limits without having to change valve stems and flow transmitter ranges.

The change in feed conditions at the start of experiments 1, 2, 5 and 6 resulted from switching feed tanks at the start of these experiments. Because of the continuous operation it was necessary to make up one tank of feed while feeding from the other and due to the time involved it was not found possible to duplicate feed concentrations exactly. Further to this, the previously mentioned heating of the feed from the feed pump and the fact that hot product was used in blending new feed made it impossible to duplicate the feed

TABLE 1-A

EXPERIMENTS

Exp. No.	Nature of Experiment
1	Open-loop response to a step up in feed rate coupled with a change in feed conditions.
2	Open-loop response to a step down in feed rate coupled with a change in feed conditions.
3	Open-loop response to a step up in steam rate, feed conditions constant.
4	Closed-loop response to a step up in feed rate, feed conditions constant.
5	Closed-loop response to a step up in feed rate coupled with a change in feed conditions.
6	Closed-loop response to a step up in concentration controller set point coupled with a change in feed conditions.
Note	During open-loop operation the steam flow controller is manually set, whereas during closed-loop operation the steam flow controller is set by the product composition controller.

TABLE 1-B

SCOPE OF EXPERIMENTS

Parameter	Minimum Value	Maximum Value
B_1	1.69 lbs./min.	2.80 lbs./min.
B_2	.96 lbs./min.	1.84 lbs./min.
C_1	4.09%	4.79%
C_2	6.48%	10.12%
Si	.94 lbs./min.	1.48 lbs./min.

temperature. Thus, a switch of feed tanks resulted in a step change in feed concentration and temperature, but since these changes could easily be incorporated into the computer simulation, the switching of tanks was made to correspond with the start of an experiment.

VII. COMPUTATIONS

About the time this project was initiated, a digital computer program called MIDAS was made available which, it was thought at the time, would allow for the solution of the model with comparable ease. This program, developed by R.T. Harnett, L.M. Warshawsky and F.J. Sansom at the Wright-Paterson Air Force Base in the United States, belongs to a class of programs called Simulator programs which allow for the solution of systems of ordinary differential equations without the programmer becoming involved in programming intricacies.

The format of MIDAS was set up so as to make its use very similar to using a very large analog computer (750 operational elements). To solve a problem, a flow diagram (very similar to an analog diagram) is drawn, but instead of wiring a patch panel, computer cards are coded, one for each operational element. The coding was very simple, involving only the identification of the operational elements and its input or inputs. For instance, if integrator 5 receives its signal from multiplier 3 the coded card would have an I5 starting in column 7 and an M3 in column 15 followed by an IC5 for the initial condition of the integrator. The benefit of this program over an analog computer is that the problem need not be scaled prior to execution and in fact the original purpose of this program was for assisting analog users with their scaling problems.

The simple method of coding and the fact that the user does not have to be concerned with logical order to the coded cards, made the use of MIDAS very appealing. Unfortunately, the computer time required for the solution of this model was found to be very much in excess of any permissible limit. Albeit the model solved via MIDAS was somewhat different than that given in this thesis, the best time that could be obtained was computer time approximately equal to real time.

The program supplied its own "variable-step, fifth-order, predict-correct" integration routine with the user being able to specify the minimum integration interval if he so desires. In spite of thus being able to keep the number of intervals at a minimum the execution time was still excessive and it can only be assumed that the internal program manipulations (i.e. sorting, checking, etc.) were the main cause of the slow execution rate.

About the time MIDAS was being dismissed as a possible vehicle for the solution of this model the developers of MIDAS issued a new simulator program called MIMIC which they claimed was 10 to 15 times more efficient than MIDAS. In spite of this increased efficiency it appeared that the computer time required to solve this model would still be excessive. Thus, it was decided that a program for the specific solution of this model would be written.

The fourth-order Runge-Kutta-Gill integration technique was selected for use in this program. Selection was based upon the fact that this technique is stable, self-

starting and easy to program. It is acknowledged that some of the many multi-step methods available might have required less computer time and possibly provided more accurate answers. However, since the calculation of derivatives for the differential equations of this model was not exceptionally tedious, it was felt that the difference in computation time between the Runge-Kutta-Gill integration method and say Hamming's predict-correct method would be small. Furthermore, experimental data could only be obtained to three figures and both of these methods supply answers at least this accurate.

A description and the derivation of the Runge-Kutta-Gill integration method will not be given in this thesis, since the subject has been well covered in numerous publications, some of which are (8, 9, 14). In this work the actual programming method was obtained from an article by M.J. Romanelli(23). Table 2 contains an outline of this method.

A major criticism of this integration method is that an estimate of the truncation error cannot easily be obtained from the calculations(23) and if a program is to contain the capacity for automatic step size adjustment, empirical techniques must be resorted to. However, in this work the object was to write a progam for the solution of a specific set of differential equations rather than a general numerical integration routine and therefore a trial and error procedure for determining the step size was deemed more economical.

TABLE 2

OUTLINE OF COMPUTATION METHOD

FOR RUNGE-KUTTA-GILL INTEGRATION

Input (i) The description of the system of (n+1) first-order differential equations

$$Y_i'(x) = F_i((Yo(x), Y_1(x), \ldots Yn(x))$$

(ii) The initial conditions

Order of Calculation

(1) Let j = 1

(2) Let i = 0

(3) Compute

$$Y_{ij}' = K_{ij} = F_i(Y_{o,j-1}, Y_{1,j-1}, \ldots Y_{n,j-1})$$

(4) Repeat step (3) for i = 1, 2, ... n

(5) Let i = 0

(6) Compute

$$Z_{ij} = A_j(K_{ij} - B_j Q_{i,j-1})$$

$$Y_{ij} = Y_{i,j-1} + hZ_{ij}$$

$$Q_{ij} = Q_{i,j-1} + 3Z_{ij} - C_j K_{ij}$$

where

$A_1 = .5$	$B_1 = 2$	$C_1 = .5$
$A_2 = 1 - \sqrt{.5}$	$B_2 = 1$	$C_2 = 1 - \sqrt{.5}$
$A_3 = 1 + \sqrt{.5}$	$B_3 = 1$	$C_3 = 1 + \sqrt{.5}$
$A_4 = 1/6$	$B_4 = 2$	$C_4 = .5$

(7) Repeat step (6) for i = 1, 2, ... n

(8) Repeat steps (2) to (7) for j = 2, 3, 4

Output

$$Y_{i4} = Y_i(xo + h)$$

The integration step size selected for these calculations was .2 min. Results produced using this step size when compared with results using a step size 10 times smaller showed agreement to 4 figures. Using a step size 10 times larger, the agreement was only to 2 figures. Moreover, since the use of a .2 min. integration interval allowed for the simulation of 180 minutes of real time in approximately 45 seconds of computer time, it was felt the use of this size of interval was justified.

As suggested earlier the calculation of derivatives for the integration routine was relatively straight-forward and thus requires no explanation here. The Fortran programs for the Runge-Kutta-Gill integration and for the calculation of derivatives can be seen in Appendix 7.

Initial conditions for the differential equations of the model were calculated by a steady state program. For any given evaporator, specification of feed conditions, (rate, concentration and enthalpy) the product composition, and the last effect vacuum or temperature completely defines the steady state of the evaporator. However, a trial and error procedure is required for balancing the material and enthalpy flows between effects and thus determine the state. A program to perform these calculations for this evaporator was written, the flow diagram for which is illustrated in Figure 15.

The required input data for this program are, besides the above mentioned parameters, values for the heat transfer coefficients and heat losses. The calculation procedure is

(1) Calculate the product from the second effect (B_2) by an overall material balance.

(2) Estimate the vaporization rate from the first effect (O_1).

(3) Calculate the first effect product rate (B_1) and composition (C_1) and the second effect vaporization (O_2) from material balances around each effect.

(4) Estimate the first effect temperature, T_1.

(5) Calculate the heat required by the second effect (Q_2) and the first effect temperature (T_1') required to transfer this heat.

(6) Do the estimated and calculated temperatures agree to within 10^{-3}°F. If not try a new guess equal to the average of these two temperatures and repeat until agreement is reached.

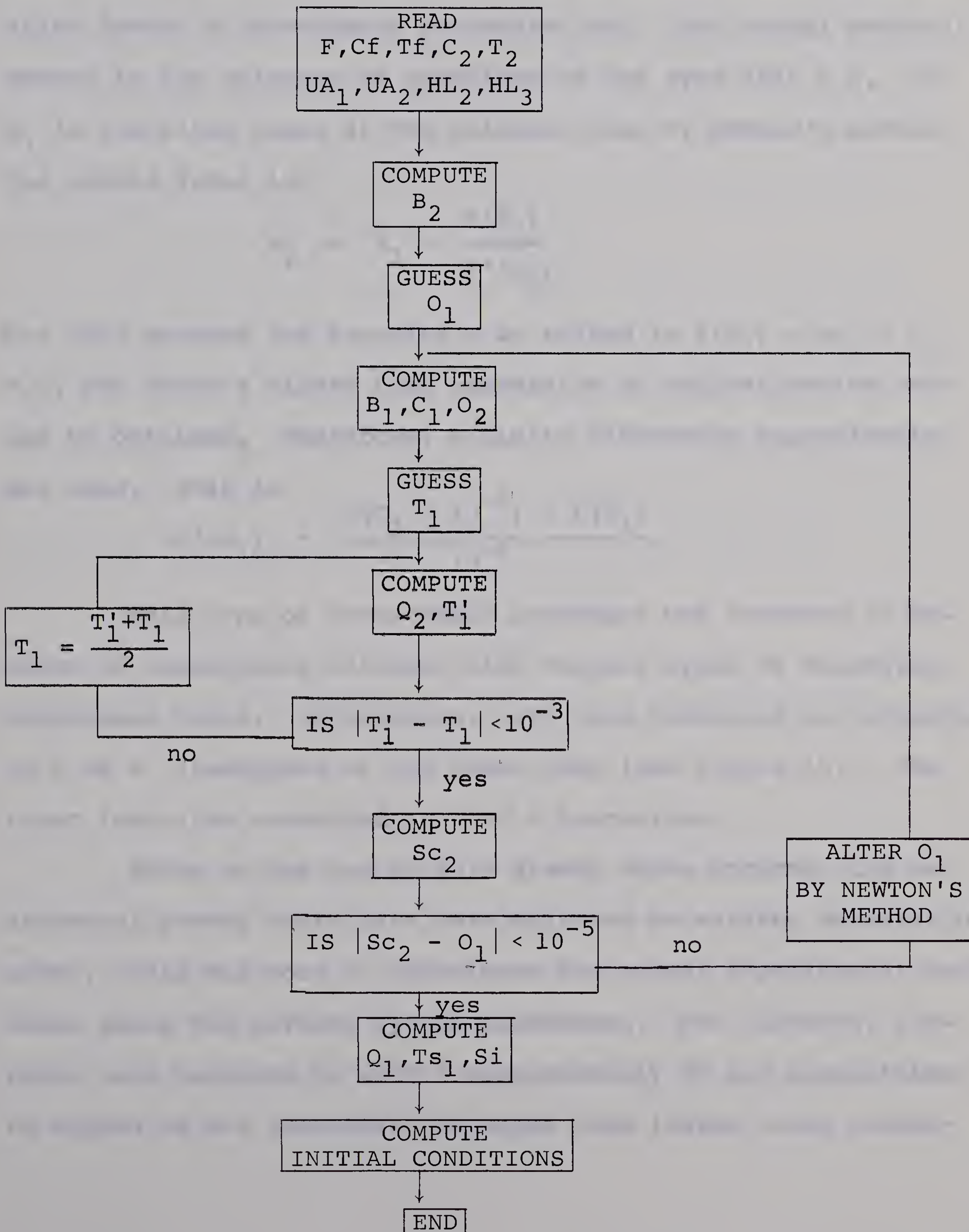
(7) Calculate the condensation rate in the steam chest of the second effect (Sc_2) required to supply Q_2.

(8) Does this condensation rate equal the estimated first effect evaporation rate to within 10^{-6} lbs./min. If not alter the estimate of O_1 by a modified Newton's method and repeat until agreement is reached.

(9) Calculate the heat required by the first effect, the steam temperature required and thus the steam rate required.

FIGURE 15

STEADY STATE PROGRAM - FLOW DIAGRAM



(10) Calculate initial conditions of all differential equations

As can be seen the calculations are straight-forward and thus require no further explanation, excepting possibly the modified Newton's convergence procedure used. The normal Newton's method is for solution of equations of the type $F(X) = 0$. If X_1 is the first guess at the solution then by Newton's method the second guess is

$$X_2 = X_1 - \frac{F(X_1)}{F'(X_1)}$$

For this program the function to be solved is $F(O_1) = Sc_2 - O_1 = 0$. for which a closed form expression of the derivative cannot be obtained. Therefore, a finite difference approximation was used. That is

$$F'(O_1) = \frac{F(O_1 + 10^{-5}) - F(O_1)}{10^{-5}}$$

This type of convergence procedure was resorted to because of convergence failures with various types of averaging techniques tried. Convergence, with this technique was achieved in 5 or 6 iterations of the outer loop (see Figure 15). The inner loop also converged in 5 or 6 iterations.

Prior to the use of this steady state program, the experimental steady state data were adjusted to satisfy material balances. This was done to distribute the normal experimental deviations among the several system parameters. For instance, flow rates were measured to within approximately 2% and compositions to within 1% and therefore the sugar flow (rates times concen-

tration) within 3%. Thus, if experimental values for feed rate, feed composition and product composition were used in the steady state program the calculated sugar flow from the first effect would be good only to 3% and therefore the disparity between calculated and experimental sugar flow could be as much as 6%. Only the data fed to the steady state programs were adjusted in this manner. The transient data reported in this thesis are unadjusted.

To adjust the data, the average sugar flow through the evaporator was calculated and the individual sugar flows adjusted so as to equal this average. It was assumed that 70% of any error is attributable to the flow rate and 30% to the concentration. For example, if SUGA is the average sugar flow then the correction applied to the feed rate was

$$\Delta F = .7 \frac{(SUGA - FCf)}{Cf}$$

and the correction applied to the feed concentration was

$$\Delta Cf = .3 \frac{(SUGA - FCf)}{F}$$

For all the experiments of this work the amount of correction was well within experimental error. The subroutine that perfomed these adjustments can be seen in Appendix 6. Shown in Appendix 8 are all the computer results which include the experimental flow rates and compositions at steady state along with the adjusted steady state data.

As mentioned in Chapter II, the estimation of heat transfer coefficients for evaporation is exceedingly difficult and experimental data is to be used wherever possible. This procedure was adopted here. After the steady state data were adjusted to satisfy material balances, the heat transfer coefficients were obtained from the resulting calculated evaporation rates and experimental temperatures. The values of the coefficients calculated in this manner showed a fair degree of scatter, up to 25%, and though an attempt was made to correlate these coefficients with temperatures and/or compositions no such correlation could be found. Therefore, in this work, the heat transfer coefficients were assumed to be constant and equal to the average of the values calculated from the steady state conditions just before and just after each experiment.

Heat losses were calculated from discrepancies in the enthalpy balances. For the first effect the heat loss was assumed to be zero since the experimental steam rate and that required according to steady state calculations showed good agreement. The discrepancy in the enthalpy balance of the second effect is made up of two heat losses, the heat loss from the vapor entering (HL_2) and the heat loss from the circulating solution (HL_3). Based upon calculations using empirical convective heat transfer coefficients and taking into account the area and mean temperatures it was established

that HL_2 is approximately 25% of HL_3 and the enthalpy balance discrepancy was divided accordingly.

In order to estimate the ramifications of errors in the above procedure (i.e. arriving at erroneous heat transfer coefficients and heat losses), four computer runs were performed in which the heat transfer coefficients and heat losses were each increased by 25% above the value calculated by the above procedure. Comparing these results to the normal results showed that these imposed errors have very little effect upon the transient behavior and in fact for the compositions the effect is negligible. The only parameters significantly affected are the temperatures. The ramification of these results is that it is unnecessary to take into account changes in these parameters during the course of an experiment since these changes never exceeded 25%. The results of these experiments are given in Appendix 9.

After the model had been completed and verified, a linearized version was developed in order to compare its results to results predicted by the non-linear model. Linearization of the original model's equations was performed in the manner shown in Chapter II. Since the value of the numerical coefficients of the linear equations depends upon the steady state conditions, a program was written which requires as input data the pertinent steady state conditions and calculates the coefficient matrix applicable to that steady state. This program is shown in Appendix 10.

More for academic interest than model verification, the model was also solved via MIMIC. The model coded for use by MIMIC is shown in Appendix 11, where it can be seen that the coding for MIMIC is fairly close to Fortran coding. The solution produced by MIMIC agreed very closely with the Fortran program solution. However, the computer time required by MIMIC was roughly 7 minutes per run as compared with 1 minute for the Fortran program. Furthermore, for MIMIC the initial conditions must first be obtained by running the steady state program and thus two computer runs are required to simulate one experiment.

VIII. RESULTS AND DISCUSSION

Figures 16 through 27 are the simulated and experimental responses of the two product compositions and product rates for each experiment, plus the simulated and experimental steam rates for the closed-loop experiments. The continuous lines are the predicted responses and the circles and triangles the experimental data. Data for the simulated curves are given in Appendix 8 and the experimental data in Tables 5-1 through 5-6 of Appendix 5.

Unfortunately, as pointed out by T.J. Williams(25), at present there is no generally accepted definition of the correctness of fit between experimental and simulated transient behavior and thus only a qualitative appraisal of these curves can be given. However, it can be seen that in general the agreement between the simulated and experimental curves is quite good, especially with regards to the concentrations.

It is felt that for the concentrations the most probable cause of the small disparities between the simulated and experimental data is a result of assuming perfect mixing of the solution in each effect. Examining the concentration curves for the open-loop experiments it can be seen that the predicted response is a little faster than the experimental response which is precisely the result one anticipates for an imperfectly mixed system(20). Due to the feed back in the closed-loop experiments, the result of imperfect mixing is

FIGURE 16 EXPERIMENT I

STEP UP IN FEED RATE, OPEN—LOOP

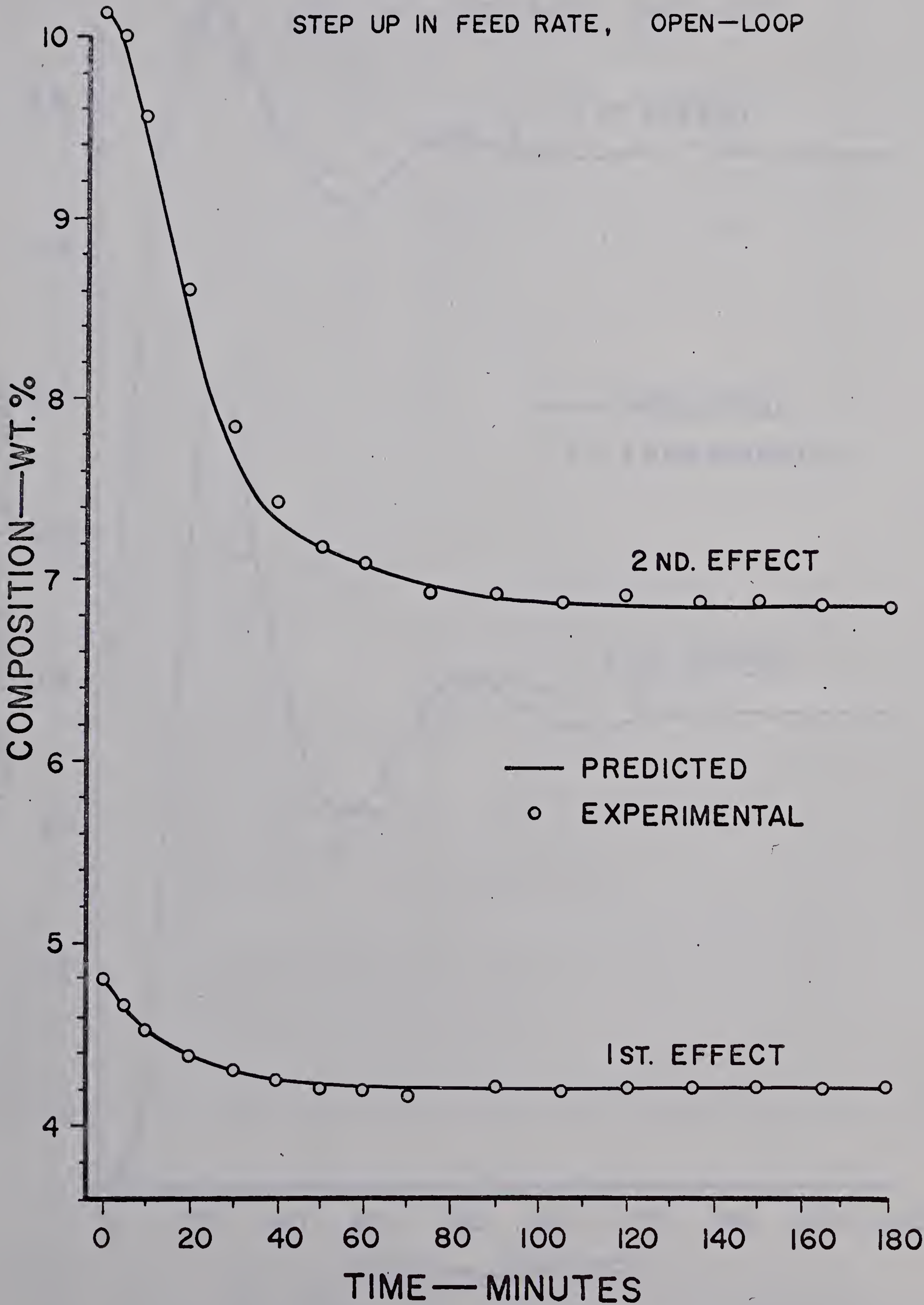


FIGURE 17 EXPERIMENT I

STEP UP IN FEED RATE, OPEN-LOOP

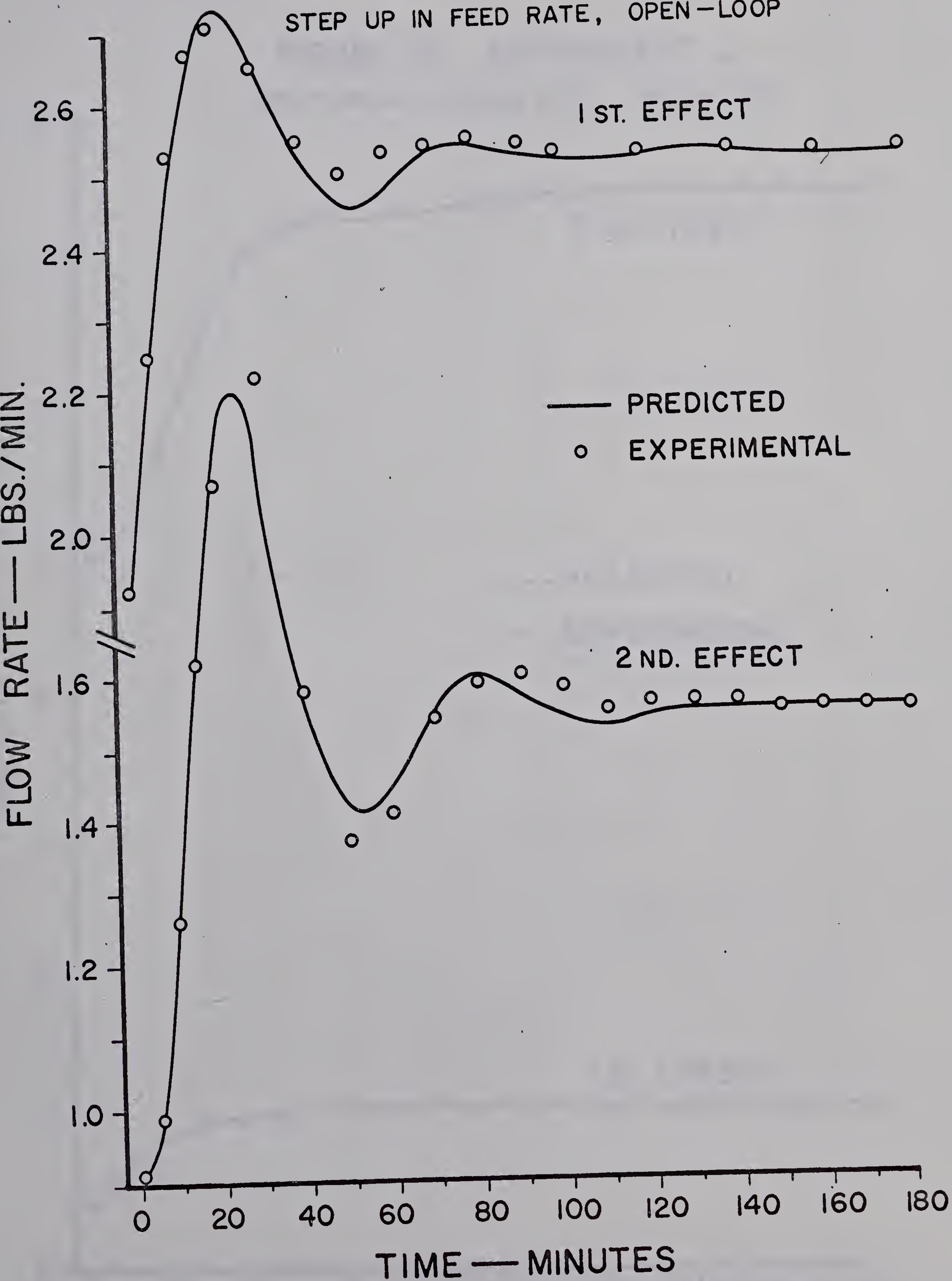


FIGURE 18 EXPERIMENT 2

STEP DOWN IN FEED RATE, OPEN-LOOP

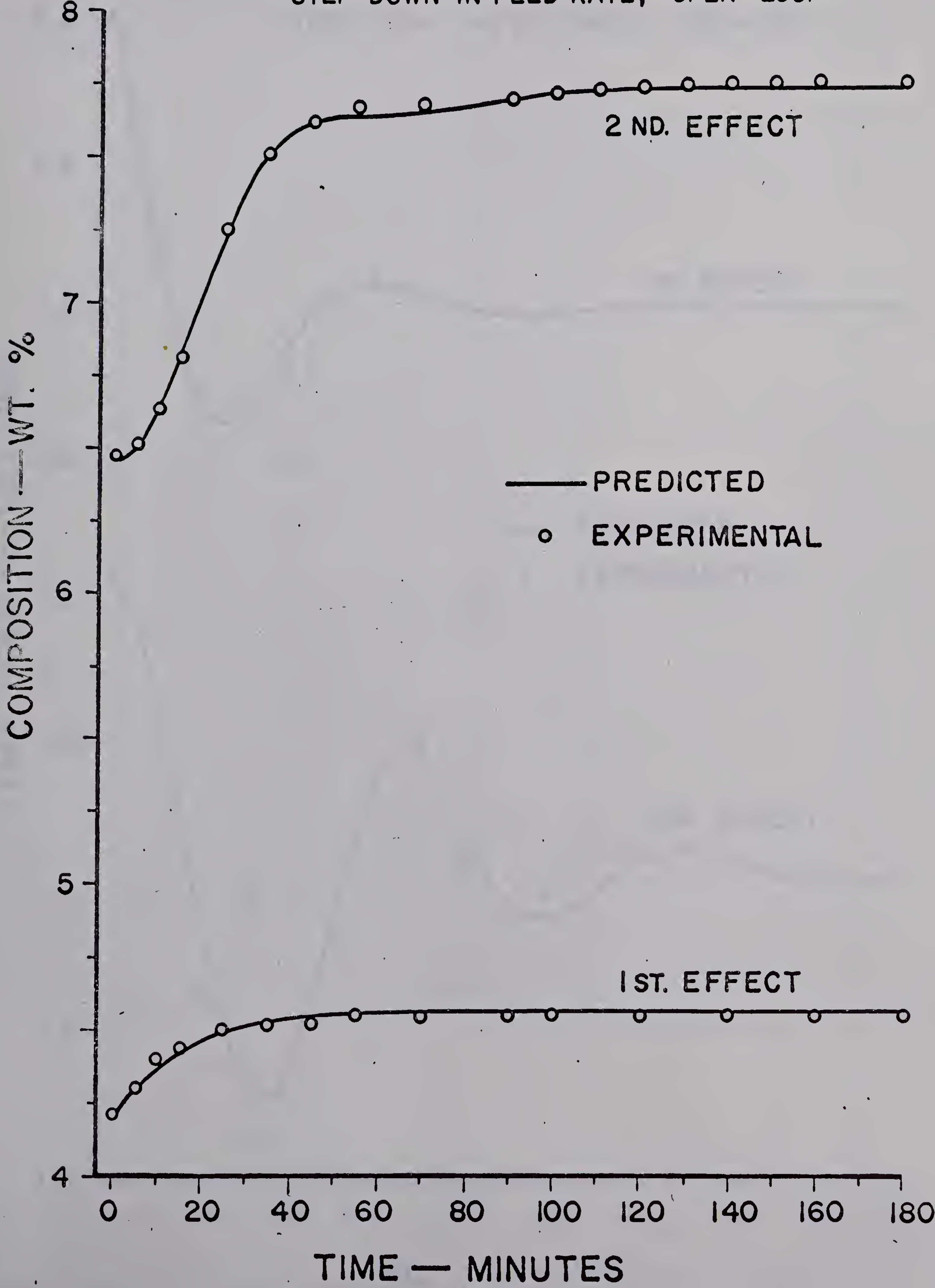


FIGURE 19 EXPERIMENT 2

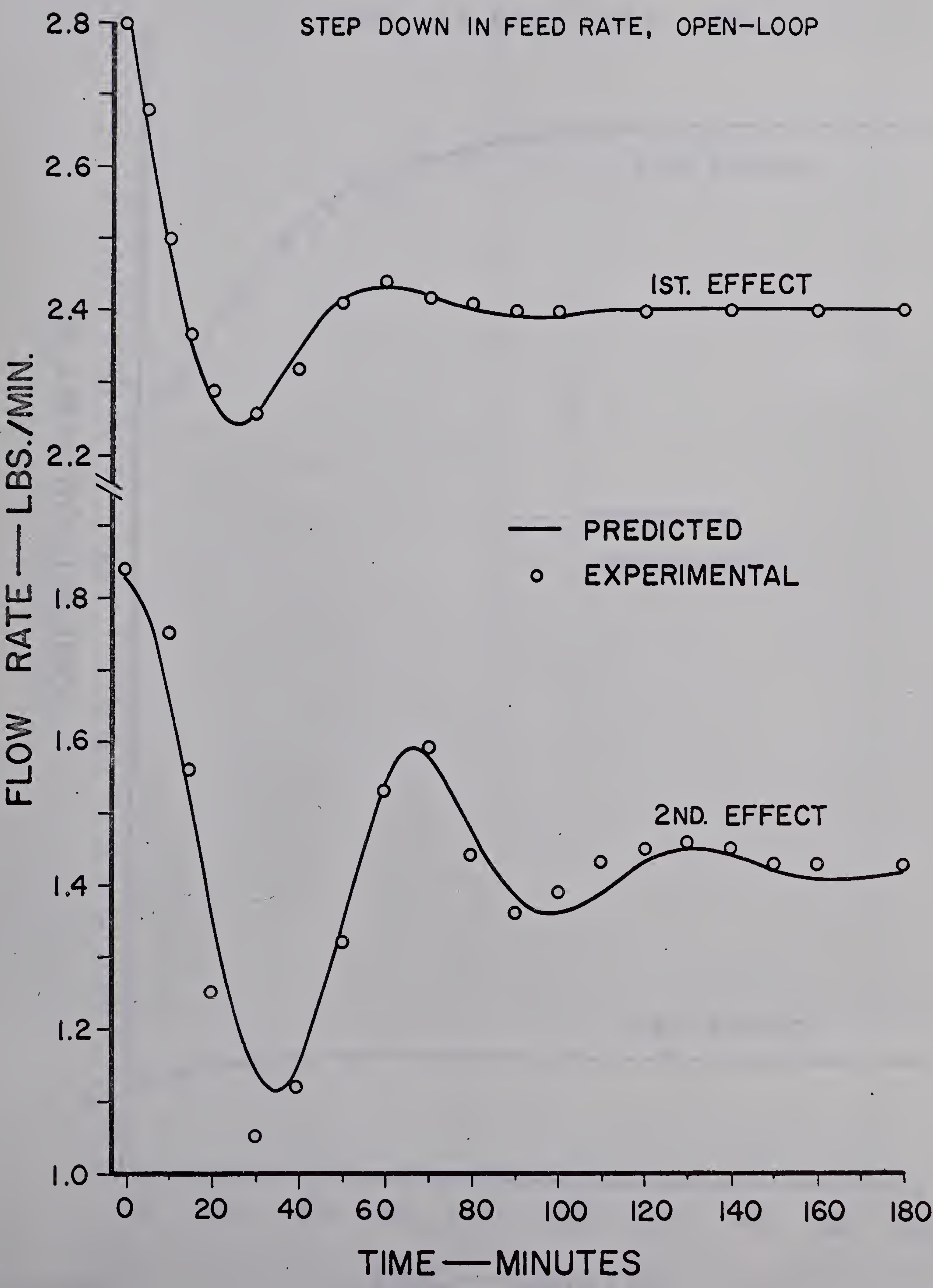


FIGURE 20 EXPERIMENT 3

STEP UP IN STEAM RATE, OPEN-LOOP

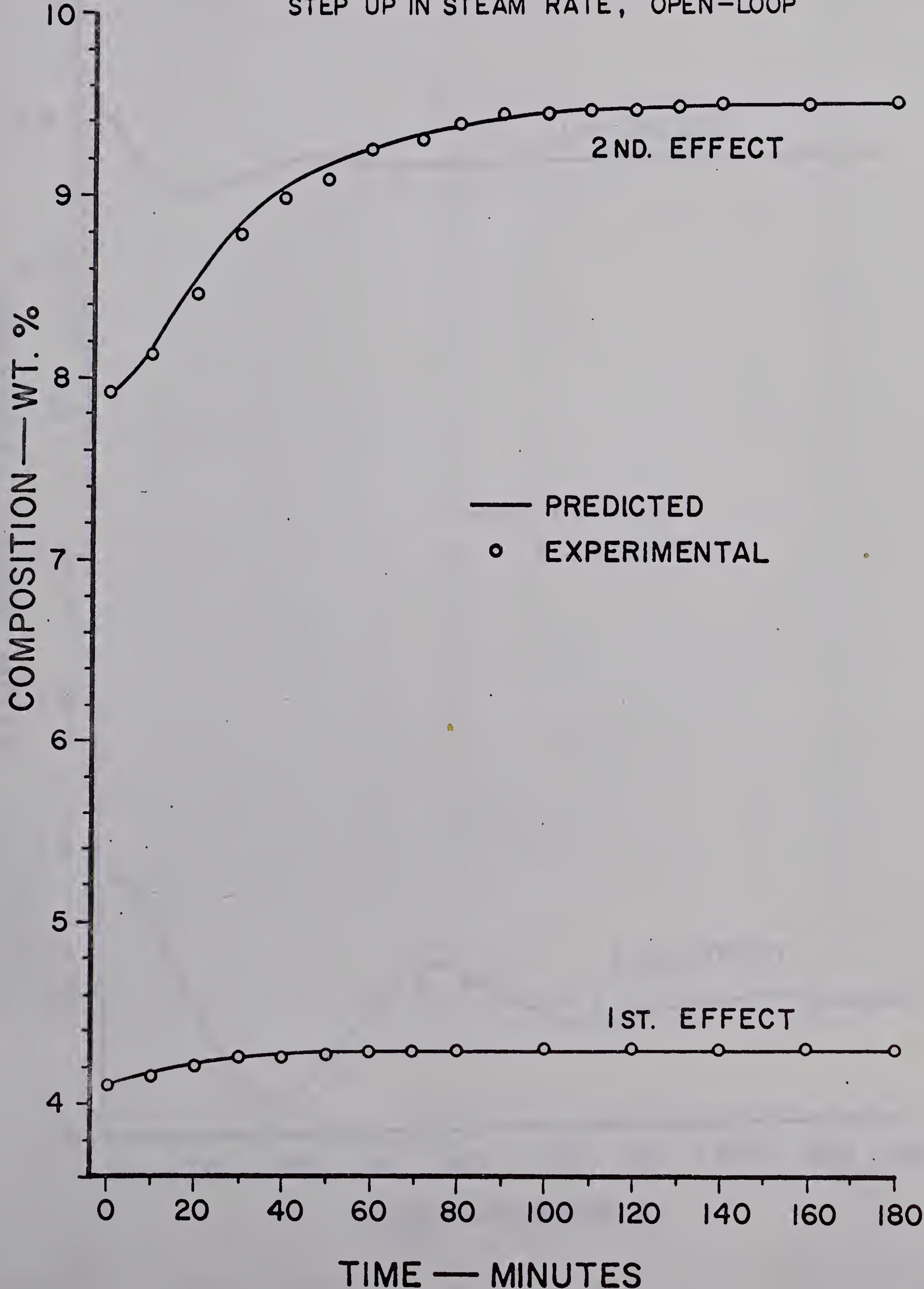
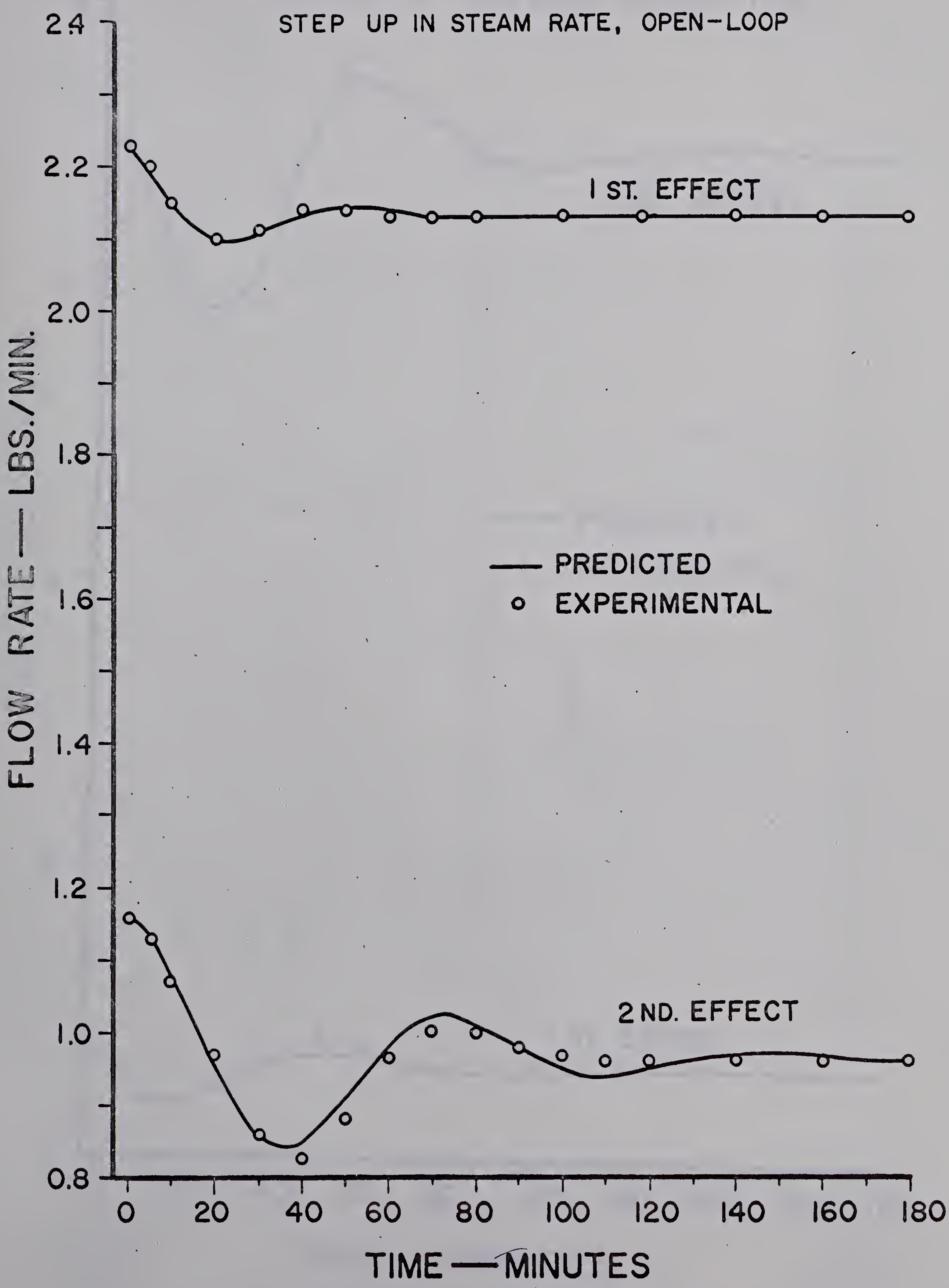


FIGURE 21 EXPERIMENT 3



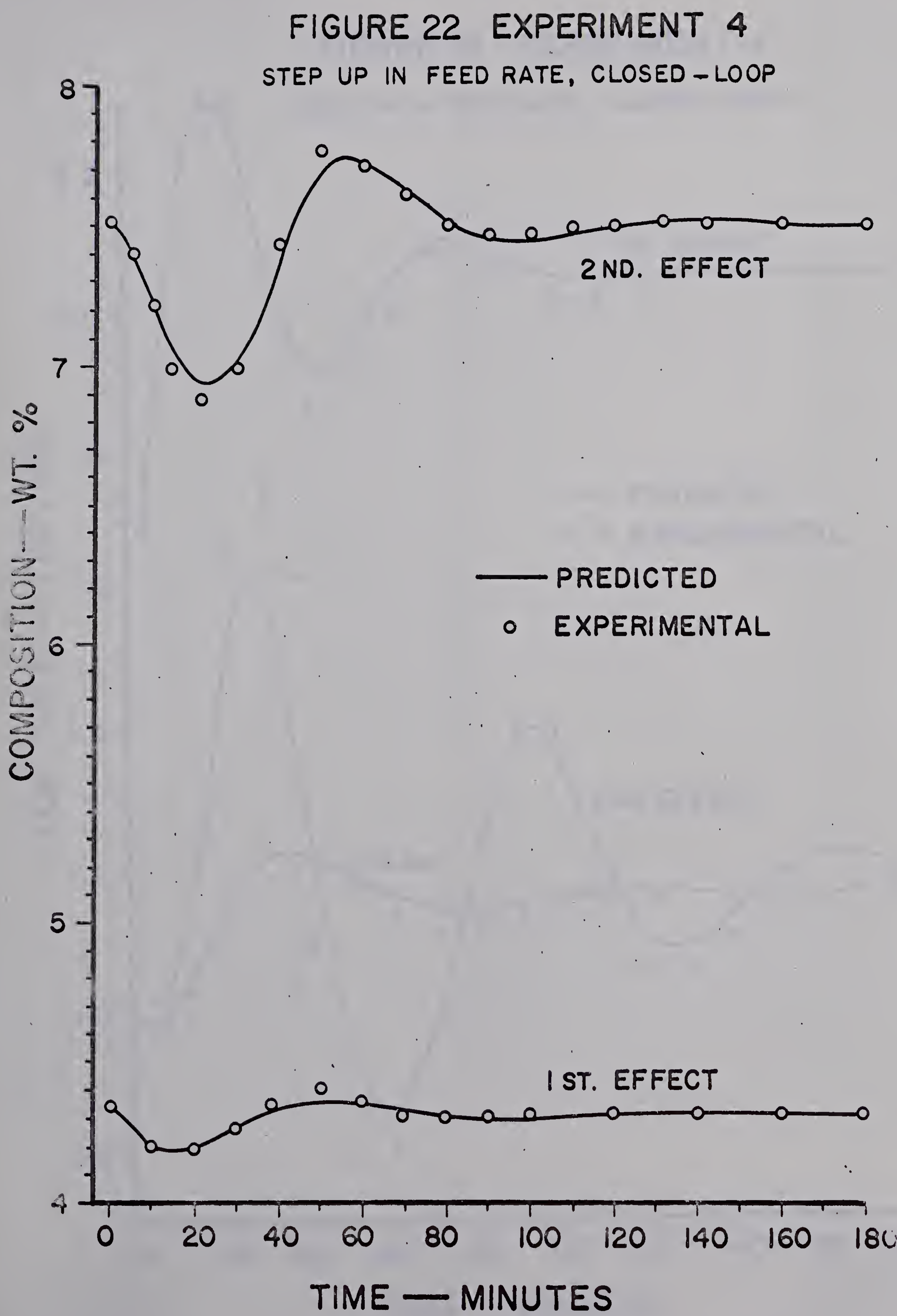


FIGURE 22 EXPERIMENT 4
STEP UP IN FEED RATE, CLOSED-LOOP
8
7
6
5
4
COMPOSITION — WT. %
2ND. EFFECT
PREDICTED
EXPERIMENTAL
I ST. EFFECT
0
20
40
60
80
100
120
140
160
180
TIME — MINUTES

FIGURE 23 EXPERIMENT 4

STEP UP IN FEED RATE, CLOSED-LOOP

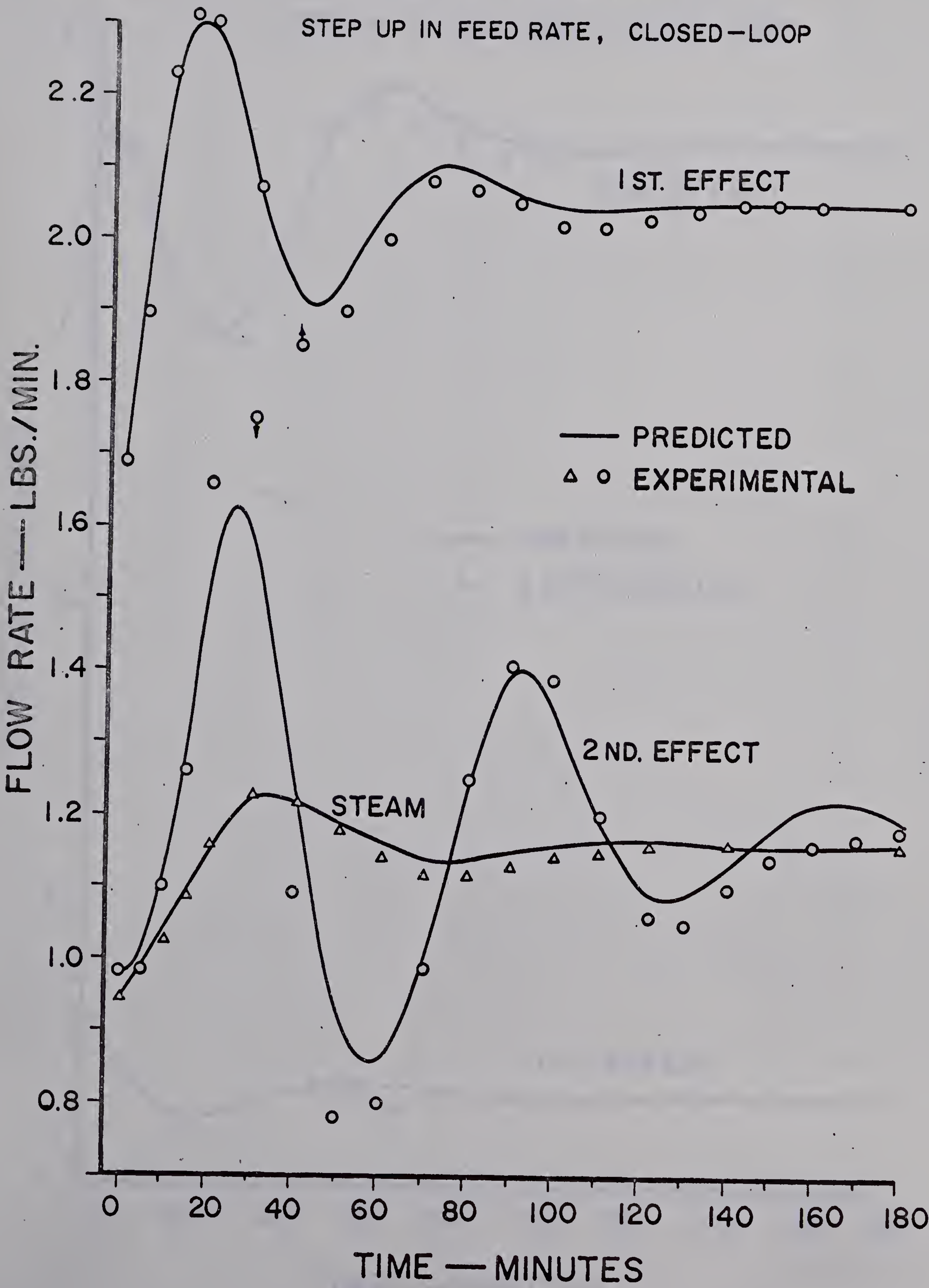
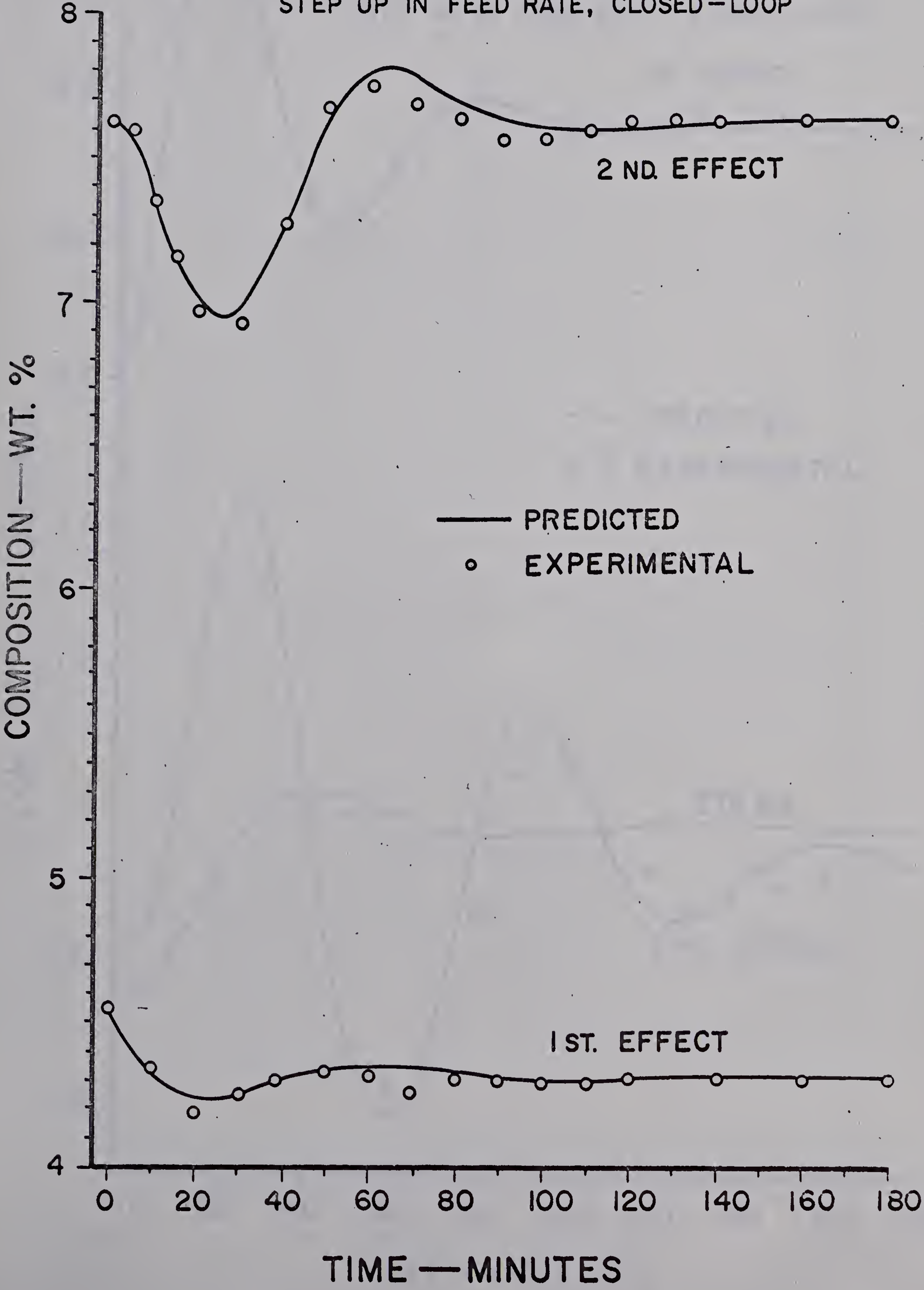


FIGURE 24 EXPERIMENT 5

STEP UP IN FEED RATE, CLOSED-LOOP



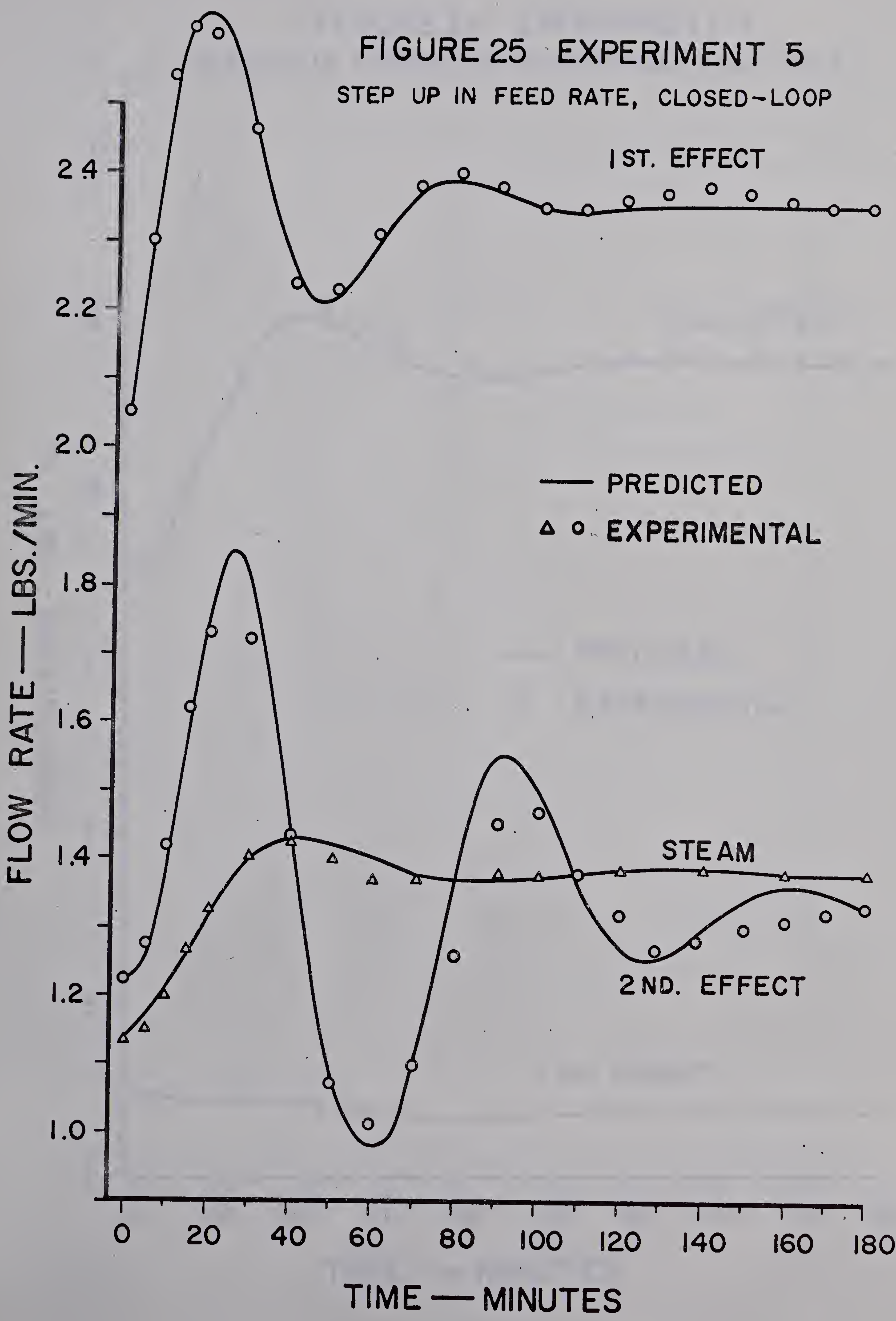


FIGURE 25 EXPERIMENT 5
STEP UP IN FEED RATE, CLOSED-LOOP
1ST. EFFECT
PREDICTED
EXPERIMENTAL
STEAM
2ND. EFFECT
FLOW RATE — LBS./MIN.
TIME — MINUTES
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0
20
40
60
80
100
120
140
160
180

FIGURE 26 EXPERIMENT 6

STEP UP IN CONCENTRATION CONTROLLER SET POINT

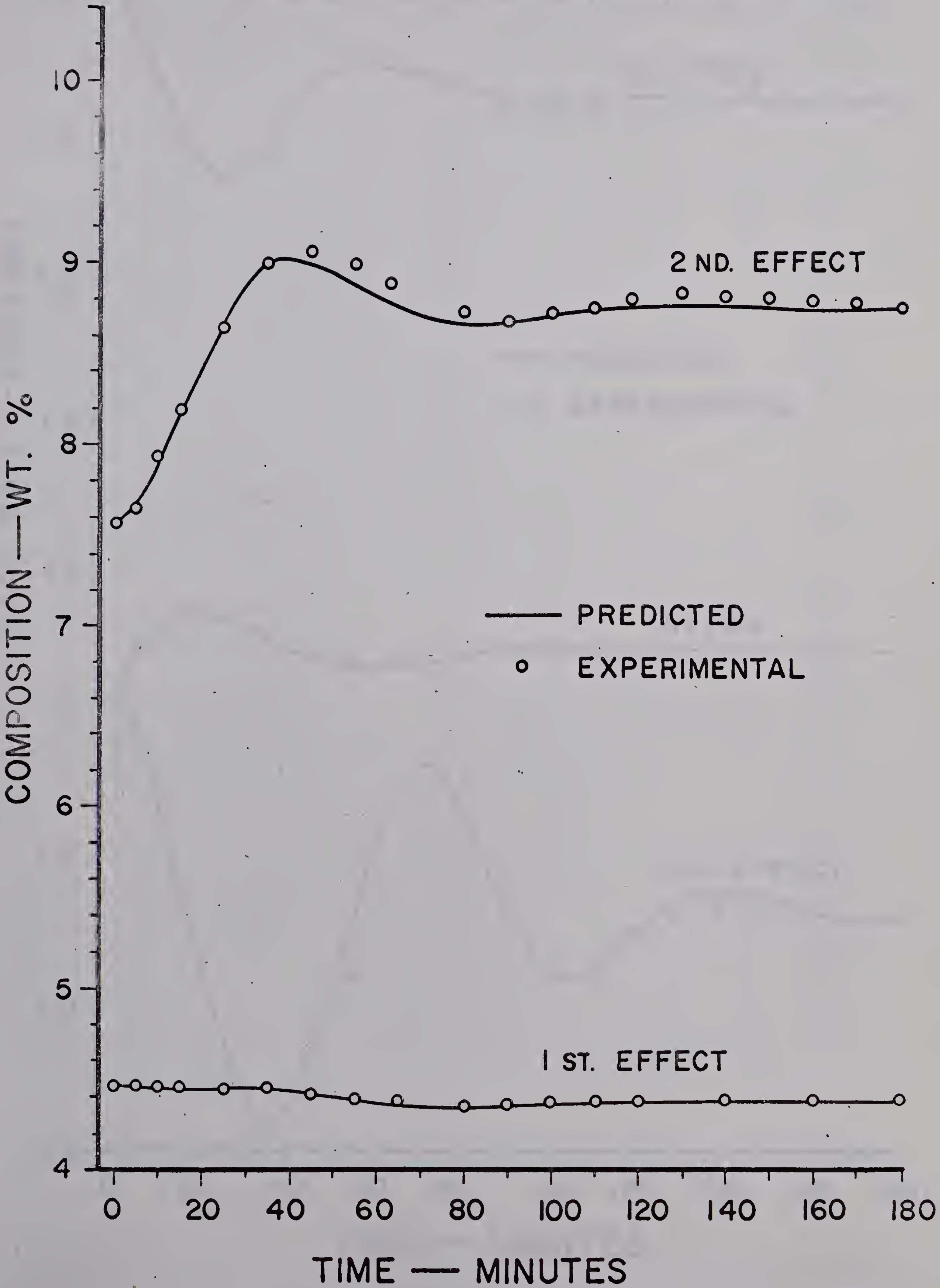
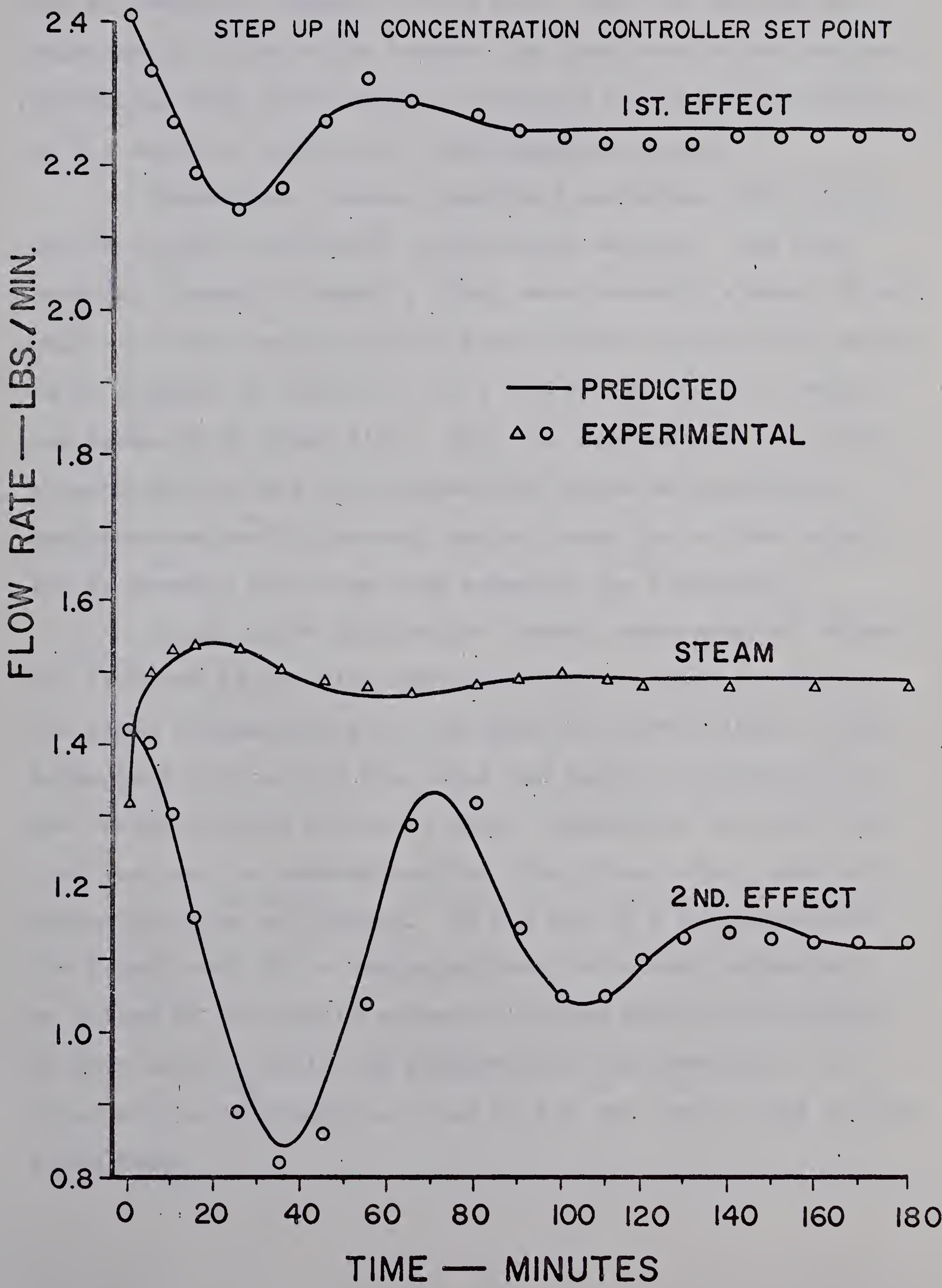


FIGURE 27 EXPERIMENT 6



not as obvious. However, it is felt, that for none of the experiments is the error between the predicted curves and experimental data large enough to warrant extensive alterations to the model to account for the imperfect mixing.

Disparities between predicted and actual flow rates can be largely attributed to the noisy records. The flow records, instead of being a line, were actually a band, 5% of chart in width, which for the first effect product flow amounted to roughly .1 lbs./min. for a 50% set point or in relative terms 4% of total flow. This is, however, not the total noise output of the flow transmitter since as previously mentioned mechanical pen-arm dampers were put on the recorders to prevent the noise from swamping the transients.

It was found that better steady state material balances resulted if the flow rate was taken to be an average of the flows corresponding to the upper and lower limits of the noise band than if the flow rate was taken to correspond to the centre line of the noise band. Therefore, the first method was used in determining the flow rates, which made data gathering twice as tedious. In the way of a recommendation for future work it is suggested that calibrated rotameters be placed in the liquid streams to allow for the calibration of flow records while the evaporator is in operation. In this way the calibrations could be for the centre line of the noise band.

Another cause of error, at least for the first effect, is an apparent change in level with changing vaporization rates. For instance, if the evaporation rate were to increase, the holdup of solution would decrease. However, for an increased vaporization rate there would be more vapor present in the ebullient solution above the steam chest and thus less space for the liquid to occupy, tending to give rise to an increase in the indicated level. The net result is that an increase in evaporation does not cause as large an indicated level decrease as that predicted by the model. However, for this evaporator, the changes in vaporization rate were not large enough to make this a serious problem and since this effect could not easily be incorporated into the model it was ignored in this work.

Although there are several other sources of error it is felt that in comparison to the noise problem all others are of minor importance and for that reason will not be discussed.

As mentioned in the previous chapter, a linearized version of the model was also developed. Experiment 4 (closed loop response to a step-up in feed rate; feed conditions constant) was simulated via this model in order to compare results predicted by the two models. The linear version was solved in exactly the same manner as the non-linear model, that is using the same Runge-Kutta-Gill integration routine.

Results produced are given in Appendix 10 and are also shown in Figures 28 and 29 along with those of the non-linear model.

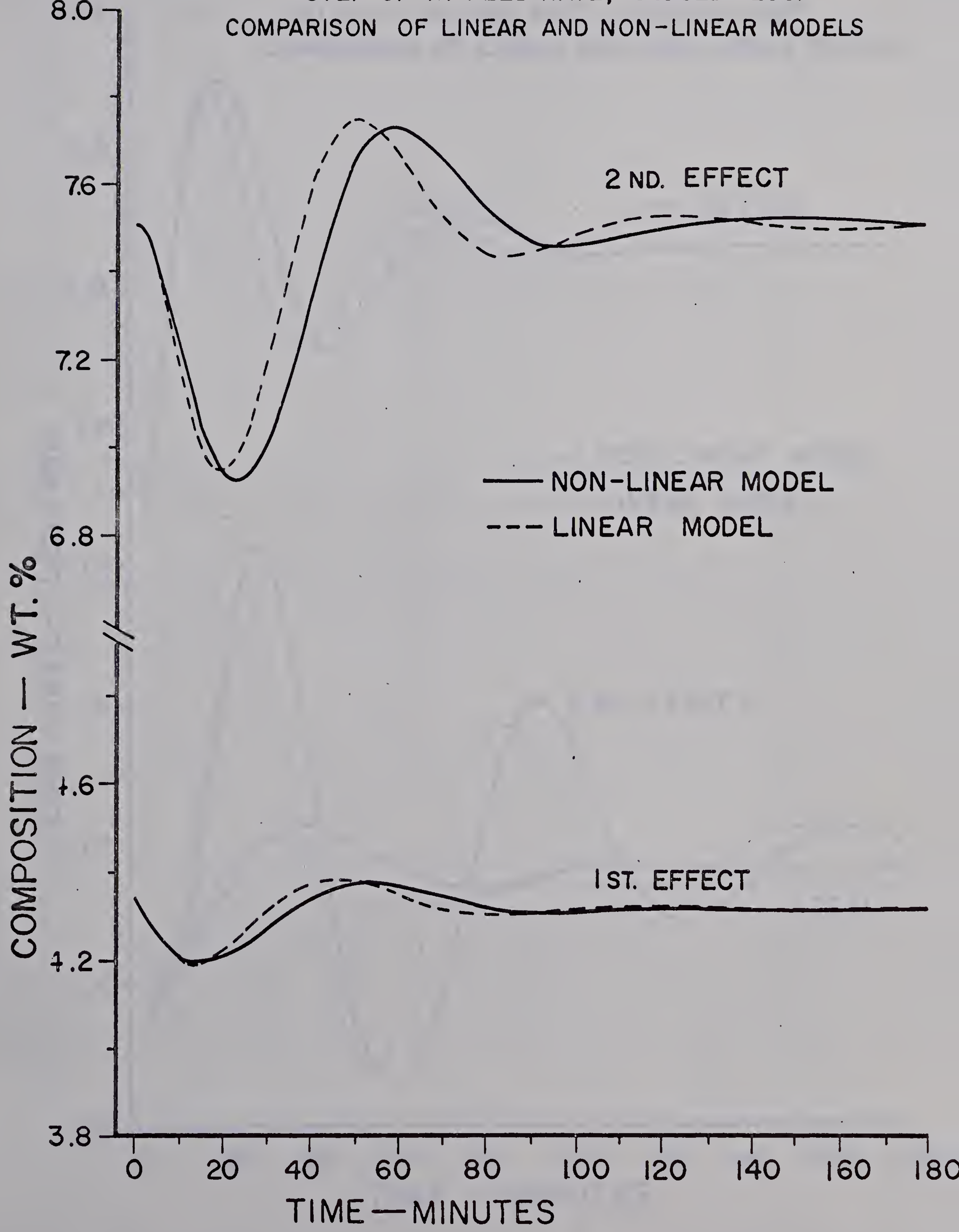
As can be seen, the results show quite good correspondence for about the first 10 minutes thereafter differing somewhat. This is, of course, not surprising since the linearization technique used is defined to be accurate only "near" the initial steady state and the step in feed has changed this state. In fact, considering that for this experiment the feed change was just over 20% it is felt that the two models show rather good agreement.

In assessing the relative merits of these two models one must consider the nature of the problem for which the model is required. For situations were perturbations to the system are not large and where rapid execution time is required it is felt the linear model can be used with some assurance. However, for problems such as the study of optimum startup and/or operating level changes the non-linear model should be used. In general, the prime assets of the linearzed model lie in the fact that a solution can be obtained quicker and that many tools of control theory and optimization require linear equations for their use. The prime assets of the non-linear model are that in theory this model is applicable for all possible operating conditions and that it is in general more accurate.

On the basis of the range of operating conditions

FIGURE 28 EXPERIMENT 4

STEP UP IN FEED RATE, CLOSED—LOOP
COMPARISON OF LINEAR AND NON-LINEAR MODELS



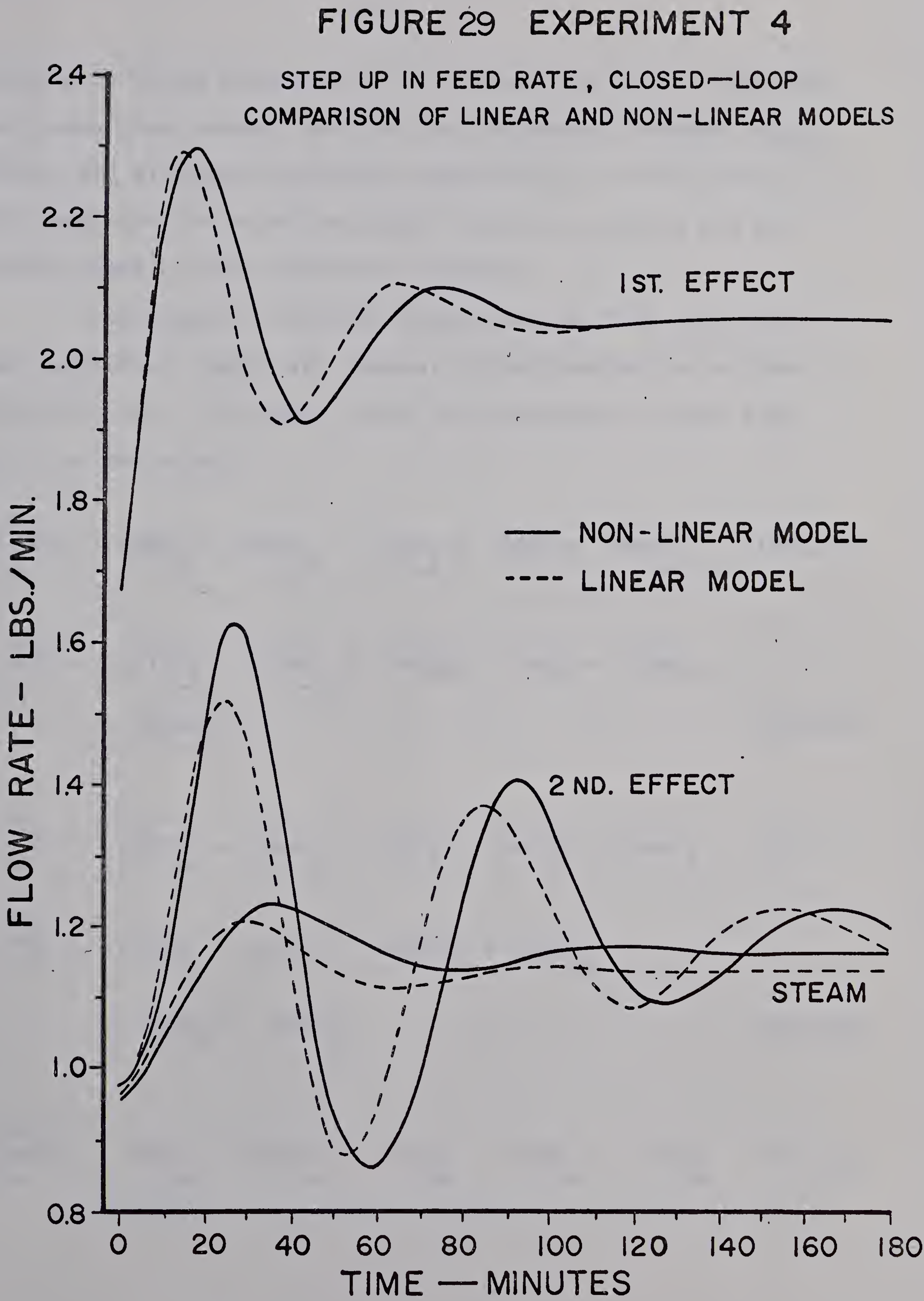


FIGURE 29 EXPERIMENT 4
STEP UP IN FEED RATE, CLOSED—LOOP
COMPARISON OF LINEAR AND NON-LINEAR MODELS
1ST. EFFECT
NON-LINEAR MODEL
LINEAR MODEL
2 ND. EFFECT
STEAM
FLOW RATE - LBS./MIN.
TIME — MINUTES
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0
20
40
60
80
100
120
140
160
180

covered by these experiments, the variety of input disturbances taken into account and the good agreement between experimental and simulated transient behavior it is felt safe to conclude that the model proposed herein is a valid and accurate model of the evaporator studied.

Although the original objectives of this work have been satisfied, there are several properties of the system worthy of note. Consider first the normalized linear equations of the model,

$$\frac{d\underline{\underline{W_1}}}{dt} = -.08\underline{H_1} - .002\underline{C_1} - .045\underline{B_1} + .065\underline{F} + .084\underline{T_2} \qquad \text{(VIII-1)}$$

$$\frac{d\underline{\underline{H_1}}}{dt} = -.571\underline{H_1} - .014\underline{C_1} + .169\underline{Si} - .040\underline{F} + .025\underline{Hf} - .563\underline{T_2} \qquad \text{(VIII-2)}$$

$$\frac{d\underline{\underline{C_1}}}{dt} = .087\underline{H_1} - .043\underline{C_1} - .020\underline{F} + .045\underline{Cf} - .084\underline{T_2} \qquad \text{(VIII-3)}$$

$$\frac{d\underline{\underline{W_2}}}{dt} = -.125\underline{H_1} - .003\underline{C_1} - .0001C_2 + .061\underline{B_1} - .036\underline{B_2} + .122\underline{T_2} \qquad \text{(VIII-4)}$$

$$\frac{d\underline{\underline{C_2}}}{dt} = .125\underline{H_1} + .039\underline{C_1} - .036\underline{C_2} - .024\underline{B_1} - .122\underline{T_2} \qquad \text{(VIII-5)}$$

where the numerical coefficients of these equations correspond to the steady state conditions prior to the start of experiment 4 and the variables are defined as deviations from this steady state. (For example, $\underline{W_1} = (W_1 - \overline{W_1}) / \overline{W_1}$, where $\overline{W_1}$ is the steady state holdup in the first effect.)

Examining these equations it is seen that the temperature of the second effect $(\underline{T_2})$ is a parameter of each equation and that the coefficients associated with $\underline{T_2}$ are all relatively large. Thus, fluctuations in $\underline{T_2}$ would have a considerable influence upon the whole system. Since the second effect temperature is determined by the second effect pressure, fluctuations in this pressure would have the same result. It is recalled that in Chapter IV precisely this effect was reported as an experimental observation. This influence of vacuum upon evaporator operation is also the effect reported by D.E. Johnson(13).

The fact that the second effect pressure has such a strong influence upon the first effect enthalpy and second effect concentration suggests the possibility of using this parameter as a manipulated variable for concentration control. However, for maximum steam economy this pressure should be controlled as low as possible and thus any decision to use this variable for control purposes would be governed by economic considerations.

Consider now equation (VIII-5). It can be seen that

the parameter having the greatest influence upon the product composition ($\underline{C_2}$) is the enthalpy of the first effect ($\underline{H_1}$). Examination of equation (VIII-2) shows that the dynamic response of this enthalpy is relatively fast (time constant = 1.75 minutes). Furthermore, with the exception of the second effect temperature, the steam rate ($\underline{Si}$) has the greatest influence upon this enthalpy. Thus, these equations show that the second effect composition responds quite rapidly to steam-rate changes. Re-examining equation (VIII-5) it is seen that the only other manipulatable variable, excluding $\underline{T_2}$, is the feed to the second effect ($\underline{B_1}$) but that the influence of this parameter upon the composition is not very large. When designing a control scheme the manipulated variable should be that variable which causes the fastest response of the controlled variable and is relatively easy to manipulate(6). Thus, the use of steam rate to control product composition is an excellent means of control and, acknowledging the possible exception of using the second effect pressure, may be the "best" choice of manipulated variable.

Although the merits of this control scheme have been discussed in relation to the evaporator of this work only, it is felt that the conclusions reached here could well be applicable to other evaporator installations. It is recalled that the relationship between steam rate and steam temperature can be expressed algebraically and therefore equation (VIII-2)

could be rewritten with $\underline{Ts_1}$, the steam temperature, replacing $\underline{Si}$. Furthermore, for a multi-effect evaporator, the enthalpy of one effect establishes the temperature in the succeeding effect. Thus, the response of the first effect enthalpy to steam temperature changes should be roughly equivalent to the response of enthalpy to the enthalpy of the preceding effect.

In terms of system parameters the influence of steam temperature upon the enthalpy is

$$\frac{\partial}{\partial Ts_1} \frac{dH_1}{dt} = \frac{U_1 A_1}{W_1} \qquad \text{(VIII-6)}$$

Also the time constant of the differential equation describing this enthalpy (IV-19) is

$$\tau = \left(\frac{\partial}{\partial H_1} \frac{dH_1}{dt}\right)^{-1} = \left(\frac{\partial}{\partial T_1} \frac{dH_1}{dt}\right)^{-1}$$

Therefore,

$$\tau = \frac{W_1}{F - .601 + U_1 A_1} \qquad \text{(VIII-7)}$$

Since the term $U_1 A_1$ is much greater in value than the other two terms in the denominator of equation (VIII-7), this equation is approximately equal to the inverse of equation (VIII-6). Thus, for other evaporators, if the ratio on the RHS of equation (VIII-6) is not significantly smaller than that of this evaporator the enthalpy of one effect will respond quickly to

changes in the enthalpy of the preceding effect. Consequently even for a multi-effect system the change in steam rate will be felt fairly quickly in the last effect and it might be that composition control by manipulating steam rate could still be superior to any other method.

It should not be construed from the previous discussion that the only merit of a dynamic model lies in its use for control-system synthesis, since this is only one area in which dynamic information is of value. In his article entitled, "Experiences and Experiments with Process Dynamics", J.O. Hougen(11) has listed other areas in which he thinks dynamic information can prove valuable. These are:

(1) To yield fundamental data useful in design and equipment scale-up.

(2) To contribute to the understanding of physical and chemical phenomena.

(3) To identify disturbances, diagnose malfunctions, reveal improper processing and supply information for advanced control schemes.

Another area of application for dynamic models not mentioned by Hougen is in system simulation. In order to simulate an entire plant, models are of course required for each of the constituent unit operations.

It is felt that the above potential applications for dynamic information provide ample justification for engaging

in process dynamics research. However, an additional motivation for this project specifically, is exemplified by the independent comments of both Hougen(11) and Williams(25), that there is a considerable need for experimental dynamic research on real systems. In fact, Williams sights evaporation in particular as being one of the unit operations for which dynamic information is lacking.

Although the model and transient data reported herein are for one evaporator specifically, this author feels that the model can be adapted for use in simulating other similar evaporators. Upon this basis it is hoped that at least a small contribution has been made to evaporator theory and indeed to process dynamics in general.

With regards to future work, some of the problems that might be studied are:

(1) Transient behavior for reverse-feed operation.

(2) Feasibility of using the last effect pressure to control concentration.

(3) Controller settings required to shape the transient response according to a predetermined optimum.

(4) Feasibility of using the control scheme employed here for evaporators of several effects.

(5) Optimize the startup procedure.

(6) Check the validity of the model for other solutions.

Needless to say there is still ample room for additional research into the dynamic behavior of evaporators.

IX. CONCLUSIONS

(1) A fully controlled 2-stage evaporator has been built and brought into operation. Although the selection of a "best" control scheme was not an original objective of this work, it is felt that the control scheme utilized on this evaporator might in some cases be superior to that stated in the literature as being most common.

(2) A mathematical model describing the transient behavior of this evaporator has been developed. For modelling purposes the evaporator was considered to be made up of several interacting sections or modules. The equations describing each section were examined as to their dynamic significance with those differential equations exhibiting a "fast" response being replaced by algebraic steady state equations. In this manner the model was simplified to where its solution was possible in reasonable computer time.

(3) The model was solved on an IBM 7040 computer using a Runge-Kutta-Gill integration routine and the simulated response compared with experimental data. In the author's opinion the degree of correspondence between predicted and experimental responses is quite good and it is therefore concluded that the model is a valid one.

(4) A linearized version of the model was developed which showed reasonable agreement with the non-linear model. Although the linear model is less accurate than the non-linear

model it is felt that for situations where linear equations are required this model can be used with a fair degree of confidence.

It should be emphasized that the validity of this model has been established for this evaporator only and before using it to analyze other similar evaporators the assumptions made in the derivation would have to be re-examined. It is felt, however, that the methods used in this work offer a relatively simple means of establishing the justifiable assumptions and thus the modification of this model for other evaporators should be quite simple.

NOMENCLATURE

A	Heat transfer area, ft^2
B	Liquid product rate, lbs./min.
C	Sugar concentration, wt. fraction
Cc	Concentration controller output, %
E	Error signal to concentration controller, %
EL	Error signal to liquid level controller, %
F	Feed rate, lbs./min.
H	Liquid enthalpy, btu/lb.
Hev	Latent heat of vaporization, btu/lb.
HL	Heat losses, btu/min.
Ho	Vapor enthalpy, btu/lb.
Hsi	Enthalpy of input steam, btu/lb.
Kc	Proportional band for concentration controller, %
KL	Proportional band for liquid level controller, %
L	Liquid level controller output, %
O	Vaporization rate, lbs./min.
Q	Heat transfer rate, btu/min.
SDENS	Square root of steam density, $(lb./ft^3)^{1/2}$
Si	Steam rate, lbs./min.
T	Temperature, ^oF
TL	Integral time for liquid level controller, min.
Tc	Integral time for concentration controller, min.
Tdc	Derivative time for liquid concentration controller, min.

U Overall heat transfer coefficient, btu/^{o}F ft^{2}min.

W Liquid holdup, lbs.

Subscripts

1 Refers to first effect

2 Refers to second effect

f Refers to feed

A bar over a quantity indicates steady state

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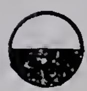
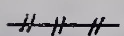
A P P E N D I C E S

APPENDIX 1

LEGEND FOR SCHEMATIC CONTROL DIAGRAMS

	CC	board mounted concentration controller
	CR	board mounted concentration recorder (2 pen)
	DVPC	board mounted differential-vapor pressure controller
	DVPT	process mounted differential-vapor pressure transmitter
	EMF	board mounted EMF-to-current transducer
	FRC	board mounted flow-recorder-controller (2 pen)
	FT	process mounted flow transmitter
	LLC	board mounted liquid level controller
	LLT	process mounted liquid level transmitter
	PRC	board mounted pressure-recorder-controller
	PT	process mounted pressure transmitter
	REF	inline refractometer

	TC	board mounted temperature controller
	TT	process mounted temperature transmitter
	TC	thermocouple
		control valve
		control valve with a valve positioner
		hand valve
----		electrical lines
		pneumatic lines
		input or output of a controller or transmitter
		recorded signal only
		external set point to a controller

APPENDIX 2

SOLENOID SWITCHING ARRANGEMENT

As mentioned in the main body of the thesis there are 2 feed tanks, a condensate tank and a solution product tank, associated with the evaporator. In order to be able to transfer material between these tanks and perform such operations as the filling, recirculating and draining of these tanks an auxiliary pump is also provided. Fifteen valves are required to control these operations, so for convenience solenoid valves were used. However, there was some concern that the accidental opening of the wrong valve could cause an experiment to be ruined. Therefore, a special switching arrangement was designed which would prevent this from occurring.

The method used was to define 16 pumping operations which could be performed with the auxiliary pump and the feed pump. These operations are;

1) Feed from tank I
2) Feed from tank II
3) Recirculate tank I
4) Recirculate tank II
5) Transfer condensate into tank I
6) Transfer condensate into tank II
7) Transfer solution product into tank I
8) Transfer solution product into tank II
9) Circulate the condensate tank

10) Circulate the product tank

11) Fill the condensate tank from an external source

12) Fill the product tank from an external source

13) Drain feed tank I

14) Drain feed tank II

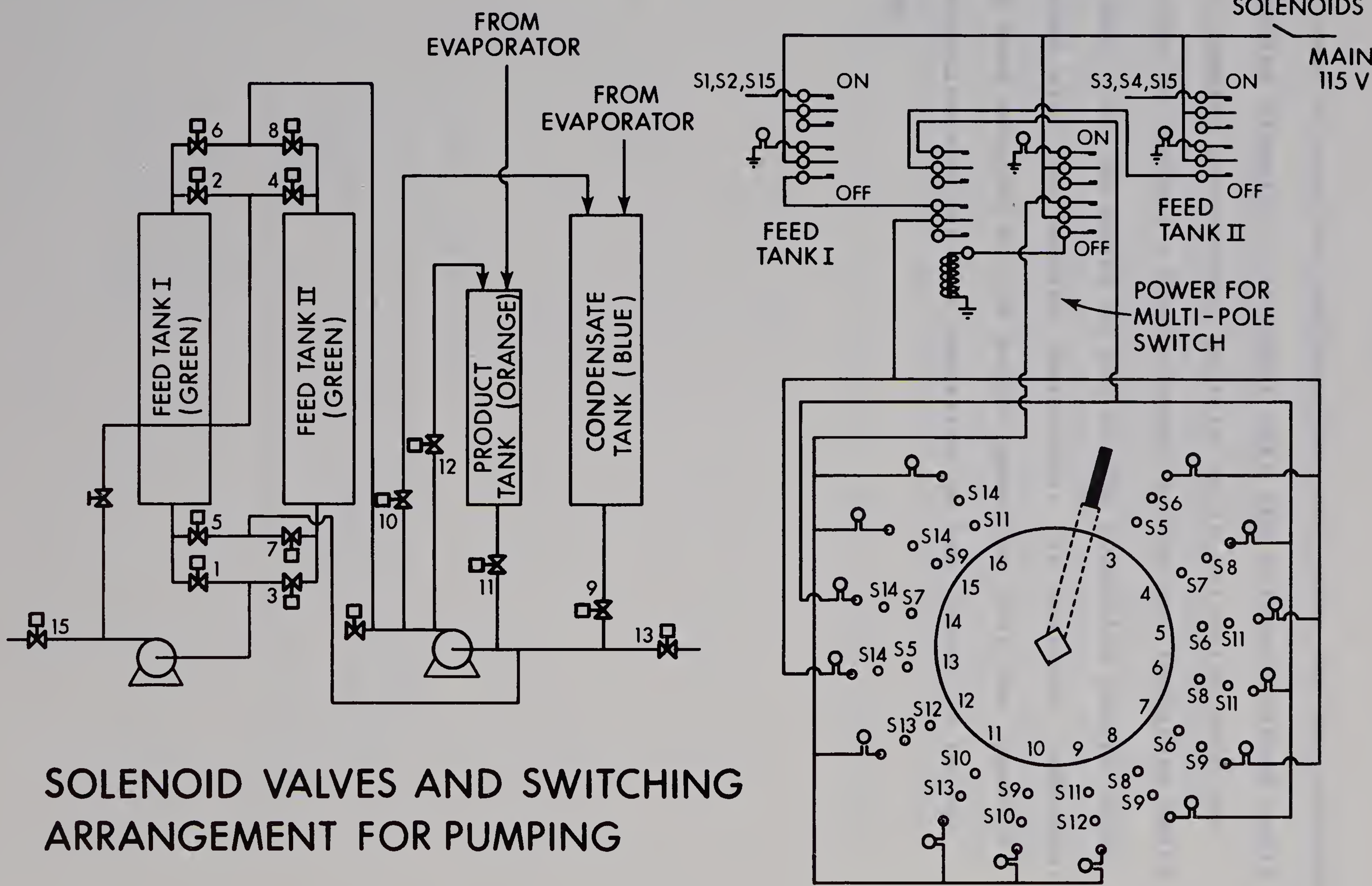
15) Drain the product tank

16) Drain the condensate tank

Operations 3 to 16 inclusive utilize the auxiliary pump and thus no two can be performed at the same time. Therefore, a multi-pole switch was wired so that location 1 to 14 correspond to operations 3 to 16. The feed pump operations 1 and 2 were controlled by separate switches. Figure 2-1 is a schematic diagram of these switches as well as the tanks and solenoid valves.

Examining this diagram it is seen that when feeding from tank I for example, solenoids 1, 2 and 15 should be open whereas solenoids 6 and 7 should not be allowed to open. In terms of operations this means operations 3, 5, 7 and 13 above are not allowed. Thus, the multi-pole was wired so that power can only get to the poles corresponding to these operations when the switch for this feed operation is off. Similarly, when feeding from tank II, operations 4, 6, 8 and 14 are not allowed and therefore the power for the solenoids of these operations must pass through the off-side of the feed switch for tank II. The other operations 9, 10, 11, 12, 15 and 16

FIGURE 2-1



SOLENOID VALVES AND SWITCHING ARRANGEMENT FOR PUMPING

are allowed at anytime and therefore the power for the solenoids is supplied directly. In order that the solenoid valves would not be opening and closing rapidly while switching from one operation to another a master power switch was installed which when shut, cut the power to all of the solenoids except those concerned with the feeding operations. In addition, indicator lights were mounted on the switch panel so that the operator can determine whether the operation he has dialed is being allowed.

APPENDIX 3

FIRST EFFECT CIRCULATION

Circulation rates were calculated using equations (IV-16) and (IV-17) which can be seen in Chapter IV. The program which was written to solve these equations is enclosed in this appendix. This program is made up of two sub-programs, the first being the main line program and the second a program to perform a linear interpolation of parameters of the equations which were fed in as numerical data. These parameters are

$$\bar{R} = f(\alpha)$$

$$\bar{r} = f(\alpha)$$

$$\left(1 - \frac{\bar{\rho}}{\rho f}\right) = f(\alpha)$$

$$fo = f(Re)$$

where

α = steam void fraction

$\bar{R}$ = correction factor for two-phase friction

$\bar{r}$ = correction factor for acceleration pressure losses

$\left(1 - \frac{\bar{\rho}}{\rho f}\right)$ = pressure drop across the pipe per foot of pipe

fo = Fanning friction factor

Re = Reynolds number

The data for these relationships were obtained from Lottes and Flinn(18) and Brown(4).

The calculation procedure is

a) estimate the circulation velocity V_i

b) calculate the circulation rate and the Reynold's number

c) calculate the steam weight fraction equal to the ratio of the evaporation rate to the circulation rate

d) using the equation of Levy(16) calculate the steam void fraction

e) determine values for all other parameters of the system and calculate the circulation velocity

f) if the calculated and estimated velocities differ by more than .1 ft./min. take an average and repeat from step b).

In this manner the velocities were calculated for vaporization rates varying from .5 to 2.0 lbs./min. and for pressures from 5 to 15 psia. The results produced are shown at the end of the program.

As can be seen the velocities show very little change over these conditions. The reason for this is that at these pressures the steam void fraction does not change to any great degree with changes in steam weight fraction. This phenomena is illustrated by Levy both theoretically and experimentally. He illustrates graphically that in the vicinity of 1 atmosphere the steam void fraction versus steam weight frac-

tion curve is nearly flat and in fact it is only at pressures in the order of 1000 psia that void fraction changes appreciably with weight fraction. The ramification of this result is that for evaporators the circulation rate remains essentially constant for all the operating conditions.

```
C
C    PROGRAM TO CALCULATE CIRCULATION RATE
C
      DIMENSION FAN(20),VEL(20),VAC(3),VAP(3),DF(20),CF1(20),CF2(20),AL(
     120),DENS(3)
      READ(5,20)(VAC(I),I=1,3)
      READ(5,19)(DENS(I),I=1,3)
      READ(5,21)(VAP(I),I=1,4)
      READ(5,22)(FAN(I),I=1,20)
      READ(5,23)(VEL(I),I=1,20)
      READ(5,24)(AL(I),I=1,14)
      READ(5,25)(CF1(I),I=1,14)
      READ(5,26)(CF2(I),I=1,14)
      READ(5,27)(DF(I),I=1,14)
      WRITE(6,10)
      DO 13 I=1,4
      DO 13 J=1,3
      O=VAP(I)
      DR=DENS(J)
      PRESS=VAC(J)
      V=100.
 2    U=4.2*V
      X=O/U
      F1=X*X
      F2=1.-X
      F3=F2*F2
      AL1=4.*F1*DR-F3-F2*SQRT(F3+8.*F1*DR)
      AL2=4.*(F1*DR-F3)
      ALPH=AL1/AL2
      RE=272.7*V
      N=0
      CALL INTERP(FAN,VEL,RE,FF,N)
      CALL INTERP(DF,AL,ALPH,DP,N)
      CALL INTERP(CF1,AL,ALPH,BR,N)
      CALL INTERP(CF2,AL,ALPH,SR,N)
      IF(N.EQ.100)GO TO 14
      VV=345600.*DP/(75.2*FF+BR*FF*24.+124.*SR)
      V1=SQRT(VV)
      IF(ABS(V1-V).LT..1)GO TO 3
      V=(V+V1)/2.
      GO TO 2
 3    WRITE(6,11)PRESS,O,V
 13   CONTINUE
 14   CONTINUE
 10   FORMAT(1HK,14X,12HPRESSURE PSI,2X,14HEVAP RATE PD/M,2X,13HVELOCITY
     1 FT/M,//)
 11   FORMAT(16X,F6.2,8X,F6.2,10X,F7.2)
 19   FORMAT(1X,3F7.1)
 20   FORMAT(1X,3F5.1)
 21   FORMAT(1X,4F4.1)
 22   FORMAT(1X,10F7.4)
 23   FORMAT(1X,8F8.1)
```

```
C
C    PROGRAM TO CALCULATE CIRCULATION RATE
C
     DIMENSION FAN(20),VEL(20),VAC(3),VAP(3),DF(20),CF1(20),CF2(20),AL(
    120),DENS(3)
     READ(5,20)(VAC(I),I=1,3)
     READ(5,19)(DENS(I),I=1,3)
     READ(5,21)(VAP(I),I=1,4)
     READ(5,22)(FAN(I),I=1,20)
     READ(5,23)(VEL(I),I=1,20)
     READ(5,24)(AL(I),I=1,14)
     READ(5,25)(CF1(I),I=1,14)
     READ(5,26)(CF2(I),I=1,14)
     READ(5,27)(DF(I),I=1,14)
     WRITE(6,10)
     DO 13 I=1,4
     DO 13 J=1,3
     O=VAP(I)
     DR=DENS(J)
     PRESS=VAC(J)
     V=100.
2    U=4.2*V
     X=O/U
     F1=X*X
     F2=1.-X
     F3=F2*F2
     AL1=4.*F1*DR-F3-F2*SQRT(F3+8.*F1*DR)
     AL2=4.*(F1*DR-F3)
     ALPH=AL1/AL2
     RE=272.7*V
     N=0
     CALL INTERP(FAN,VEL,RE,FF,N)
     CALL INTERP(DF,AL,ALPH,DP,N)
     CALL INTERP(CF1,AL,ALPH,BR,N)
     CALL INTERP(CF2,AL,ALPH,SR,N)
     IF(N.EQ.100)GO TO 14
     VV=345600.*DP/(75.2*FF+BR*FF*24.+124.*SR)
     V1=SQRT(VV)
     IF(ABS(V1-V).LT..1)GO TO 3
     V=(V+V1)/2.
     GO TO 2
3    WRITE(6,11)PRESS,O,V
13   CONTINUE
14   CONTINUE
10   FORMAT(1HK,14X,12HPRESSURE PSI,2X,14HEVAP RATE PD/M,2X,13HVELOCITY
    1 FT/M,//)
11   FORMAT(16X,F6.2,8X,F6.2,10X,F7.2)
19   FORMAT(1X,3F7.1)
20   FORMAT(1X,3F5.1)
21   FORMAT(1X,4F4.1)
22   FORMAT(1X,10F7.4)
23   FORMAT(1X,8F8.1)
```

```
24    FORMAT(1X,15F4.2)
25    FORMAT(1X,10F5.2)
26    FORMAT(1X,10F7.4)
27    FORMAT(1X,10F6.3)
      END
```

```
      SUBROUTINE INTERP(Y,X,Z,R,N)
      DIMENSION Y(20),X(20)
      N=N+1
      IF(Z.LT.X(1))GO TO 3
      DO 5 I=1,20
      IF(Z.GT.X(I))GO TO 5
      R=Y(I-1)+(Y(I)-Y(I-1))*(Z-X(I-1))/(X(I)-X(I-1))
      GO TO 12
5     CONTINUE
      WRITE(6,10)N
      N=100
      GO TO 12
3     WRITE(6,11)N
      N=100
12    CONTINUE
      RETURN
10    FORMAT(1X,14HEXCEEDED RANGE,I4)
11    FORMAT(1X,11HBELOW RANGE,I4)
      END
```

```
      SUBROUTINE INTERP(Y,X,Z,R,N)
      DIMENSION Y(20),X(20)
      N=N+1
      IF(Z.LT.X(1))GO TO 3
      DO 5 I=1,20
      IF(Z.GT.X(I))GO TO 5
      R=Y(I-1)+(Y(I)-Y(I-1))*(Z-X(I-1))/(X(I)-X(I-1))
      GO TO 12
5     CONTINUE
      WRITE(6,10)N
      N=100
      GO TO 12
3     WRITE(6,11)N
      N=100
12    CONTINUE
      RETURN
10    FORMAT(1X,14HEXCEEDED RANGE,I4)
11    FORMAT(1X,11HBELOW RANGE,I4)
      END
```

PRESSURE PSI	EVAP RATE PD/M	VELOCITY FT/M
5.00	0.50	131.41
10.00	0.50	131.42
15.00	0.50	131.42
5.00	1.00	131.37
10.00	1.00	131.39
15.00	1.00	131.40
5.00	1.50	131.31
10.00	1.50	131.36
15.00	1.50	131.38
5.00	2.00	131.24
10.00	2.00	131.32
15.00	2.00	131.35

APPENDIX 4

CALIBRATION CURVES

The calibration curves for all of the flow transmitters are shown in Figures 4-1 to 4-7 inclusive. These figures are self-explanatory and thus need not be discussed further. However, for the model, a mathematical expression of steam flow and first effect product flow curves are required.

It was mentioned in the main body of the thesis that calibration shifts in the first effect product flow made it necessary to recalibrate this stream. Figures 4-2, 4-3 and 4-4 are the three calibration curves. For the model it was assumed that one calibration held for all the experiments and when the calibration points were drawn on one graph the equation of the "best"-fit line through these points was found to be

$$B = 1.33 \left(\frac{CR}{10}\right)^{.481} \qquad (4\text{-}1)$$

where CR = chart reading in percent. The flow controller regulating this stream and the recorder were adjusted so that the chart reading in percent corresponded to the set point in percent. Thus, equation (4-1) could be used directly in the model with the controller set point (L_1) substituted for CR. The equations for the individual calibration curves did not differ enough from the above average equation to warrant incorporating all three equations into the model.

FIGURE 4-1

CALIBRATION CURVE

FEED FLOW

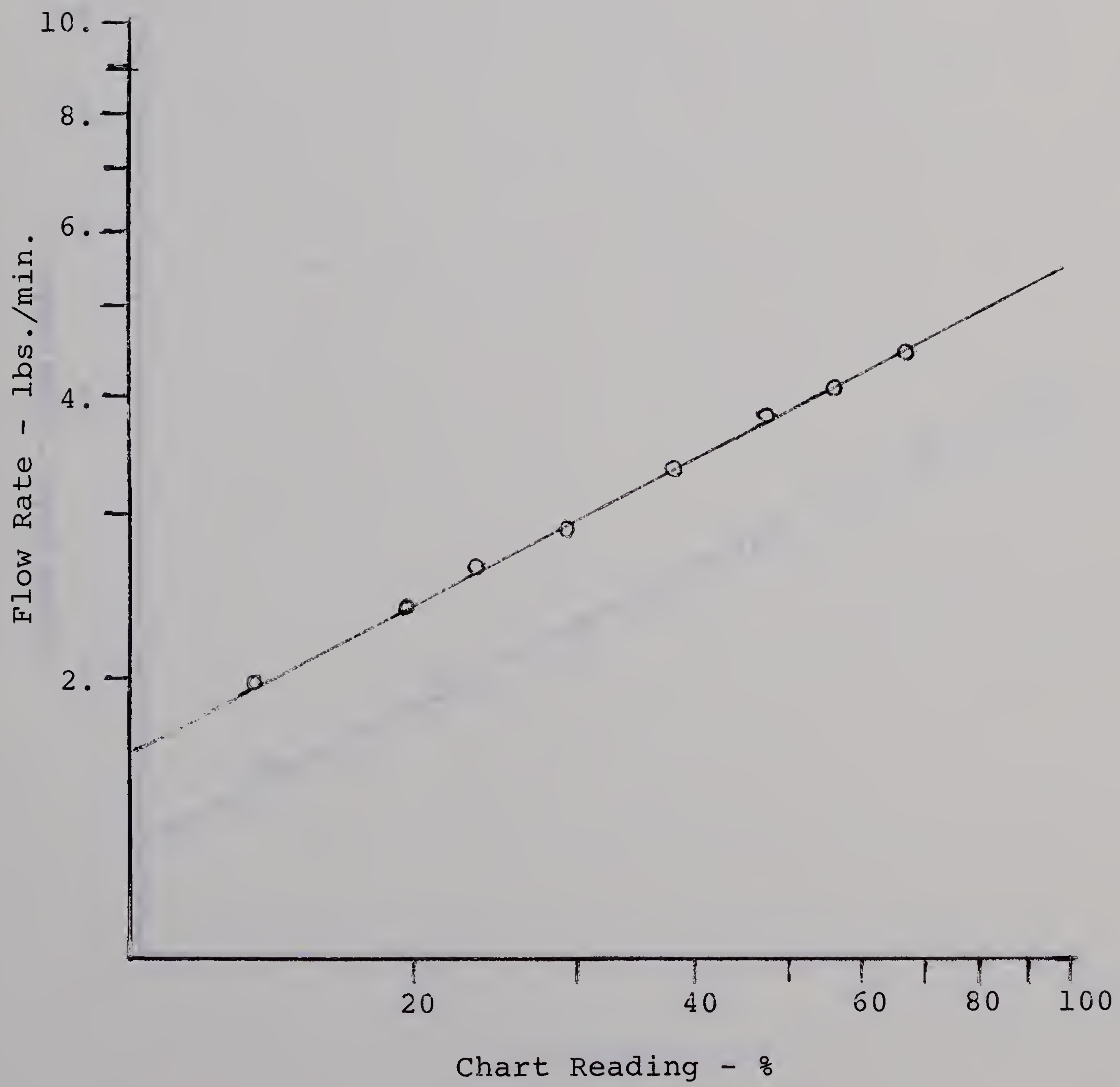


FIGURE 4-2

CALIBRATION CURVE

FIRST EFFECT PRODUCT RATE

EXPERIMENT 1

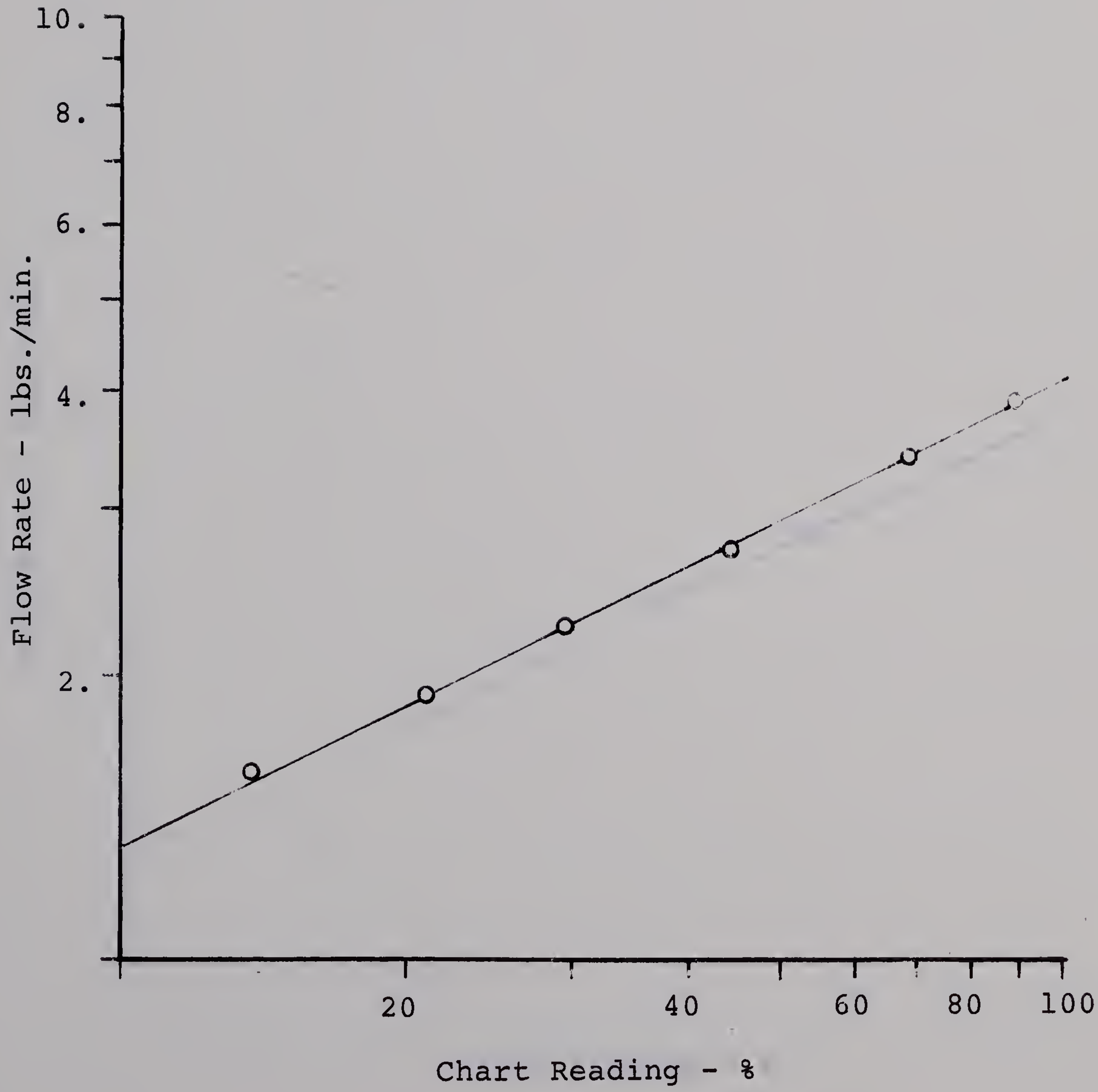


FIGURE 4-3

CALIBRATION CURVE

FIRST EFFECT PRODUCT RATE

EXPERIMENT 2, 3

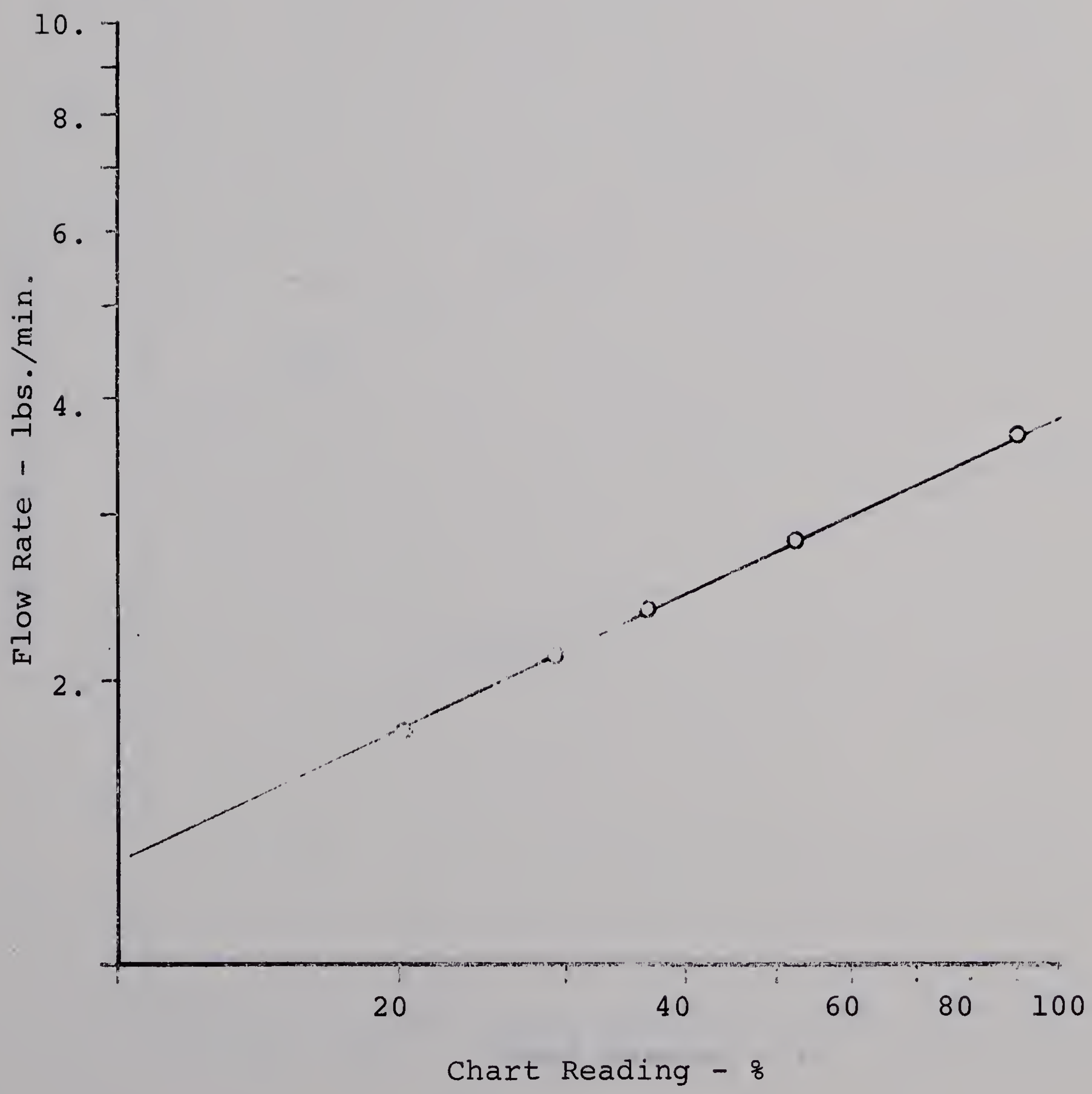
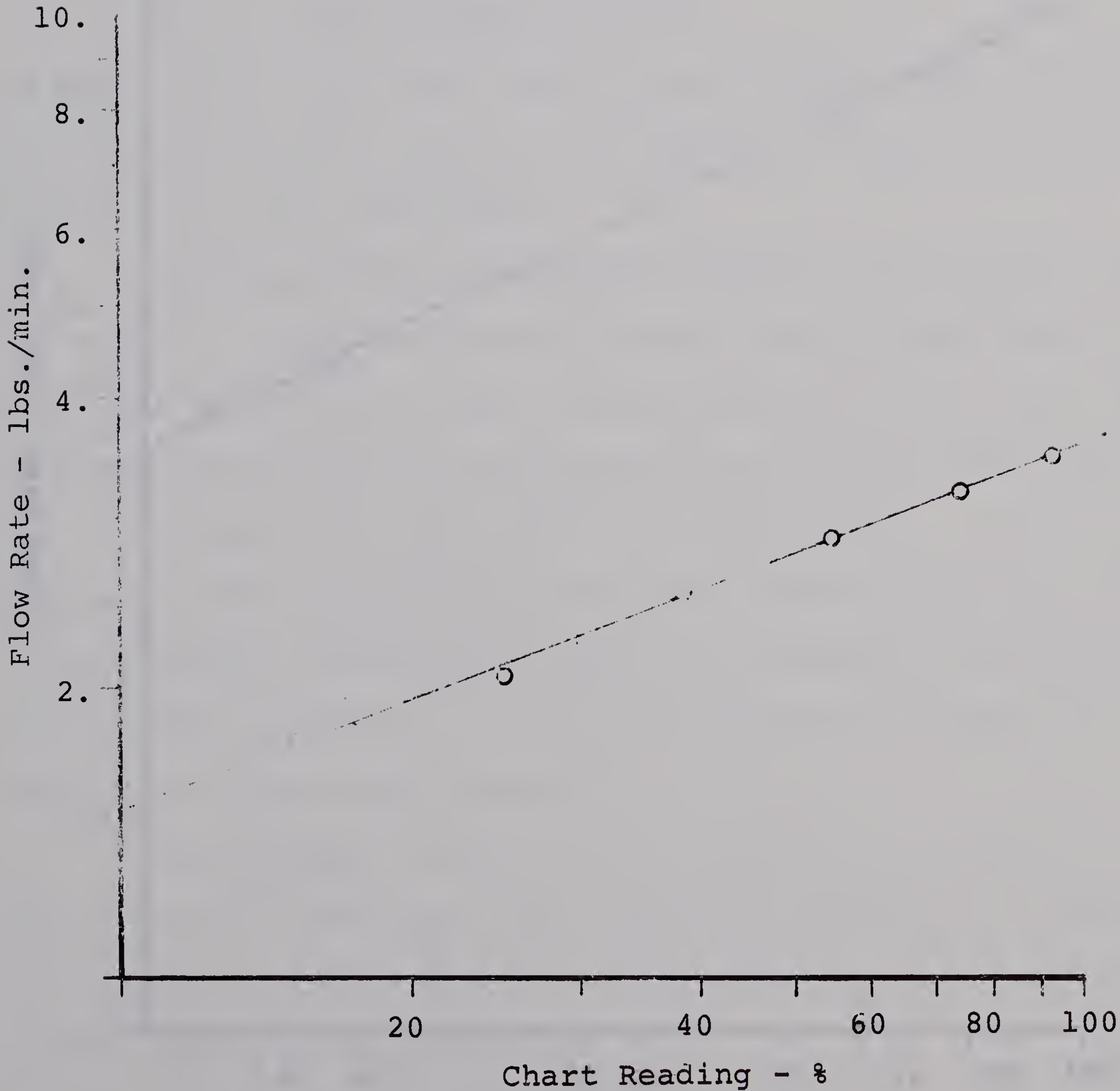


FIGURE 4-4

CALIBRATION CURVE

FIRST EFFECT PRODUCT RATE

EXPERIMENT 4, 5, 6



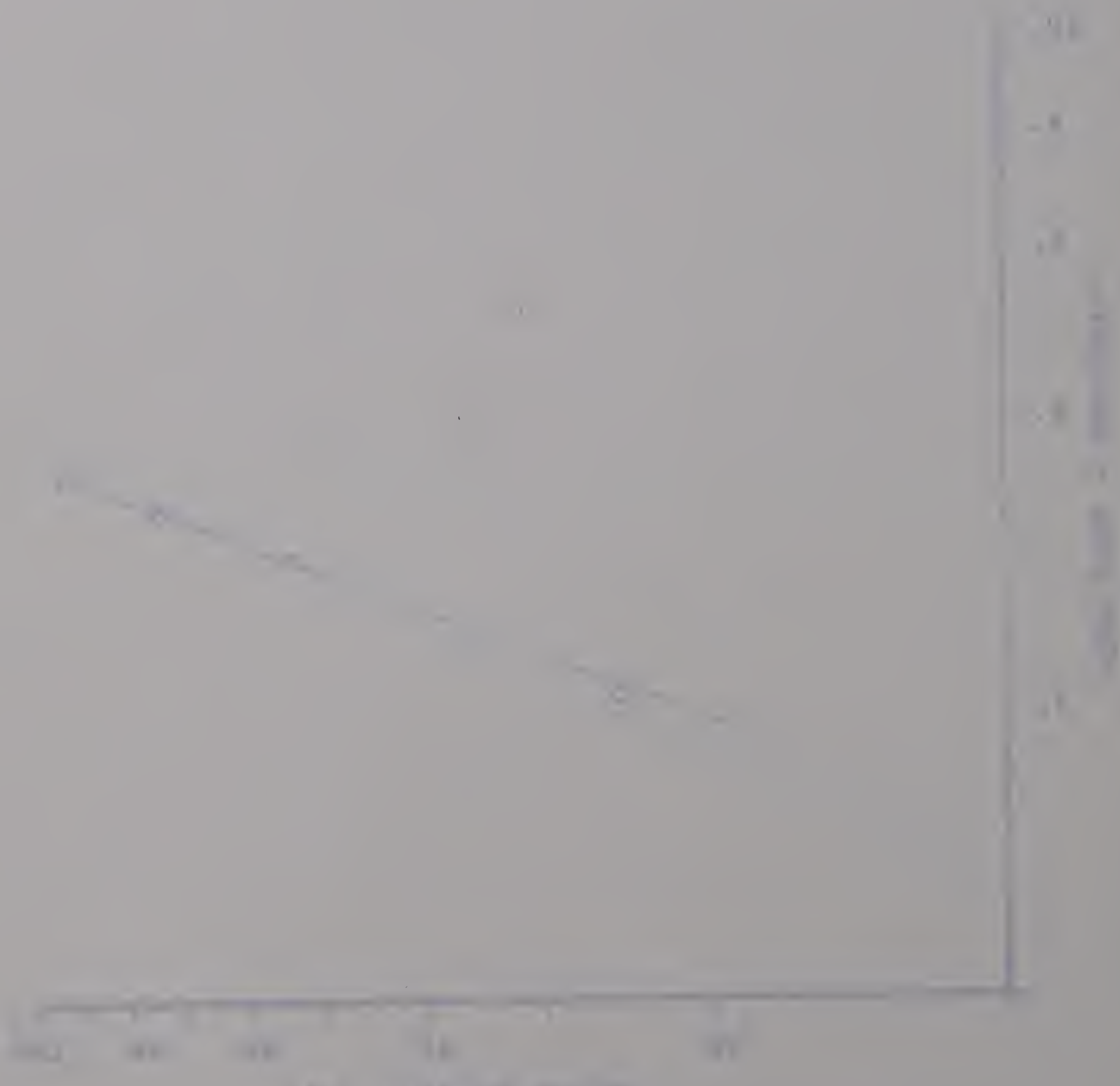


FIGURE 4-5

CALIBRATION CURVE

SECOND EFFECT PRODUCT RATE

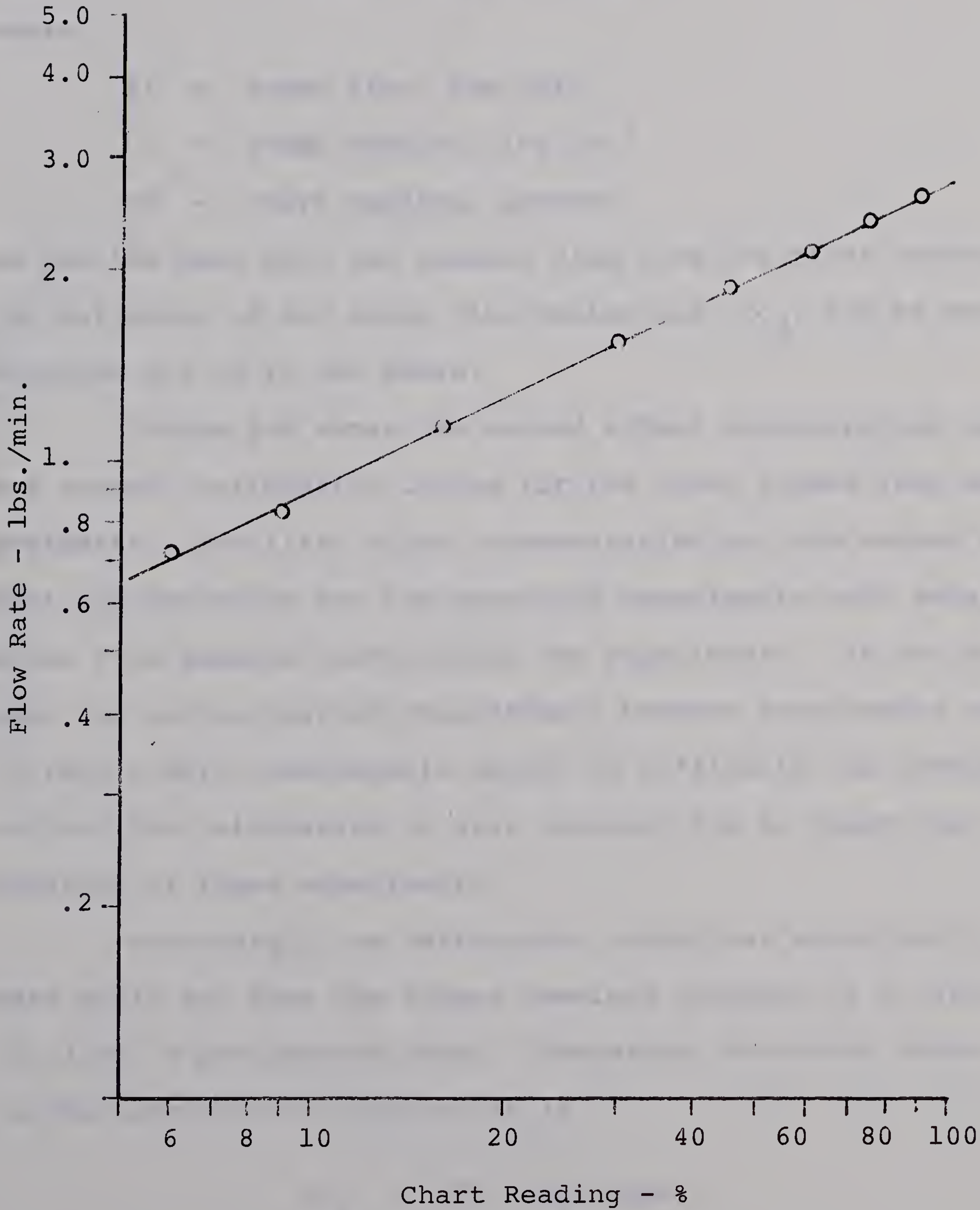


Figure 4-6 is the steam flow calibration curve, the equation for which is

$$Si = .68 \sqrt{\rho}\ (CR)^{.455}$$

where

Si = steam flow, lbs./min.

ρ = steam density, lbs./ft^2

CR = chart reading, percent

As was the case with the product flow from the first effect, the set point of the steam flow controller (Cc_2) can be substituted for CR in the above.

Figure 4-8 shows the second effect concentration versus record, calibration curves for the three closed-loop experiments. The first effect concentration and the second effect concentration for the open-loop experiments were determined from samples taken during the experiments. As can be seen the curves shifted considerably between experiments and in fact a very considerable amount of difficulty was encountered getting the calibration to stay constant for at least the duration of these experiments.

Fortunately the calibration change was essentially a zero shift and thus the slopes remained constant at a value of .1 wt. % per percent chart. Therefore, the error signal to the concentration controller is

$$Ec_2 = (\overline{C}_2 - C_2)\ 1000.$$

FIGURE 4-6

CALIBRATION CURVE

STEAM FLOW

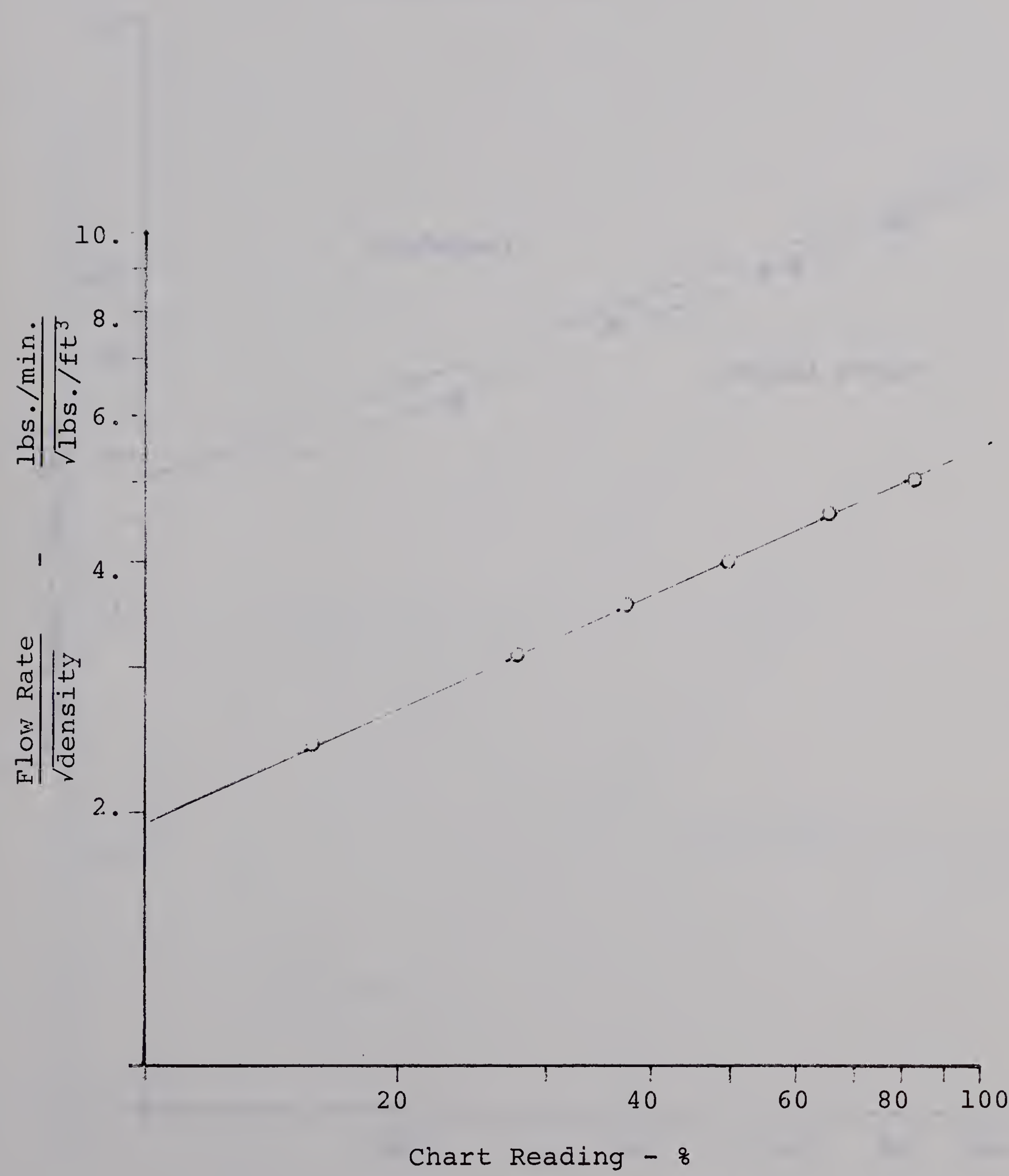


FIGURE 4-7

CALIBRATION CURVES

CONDENSATE FLOWS

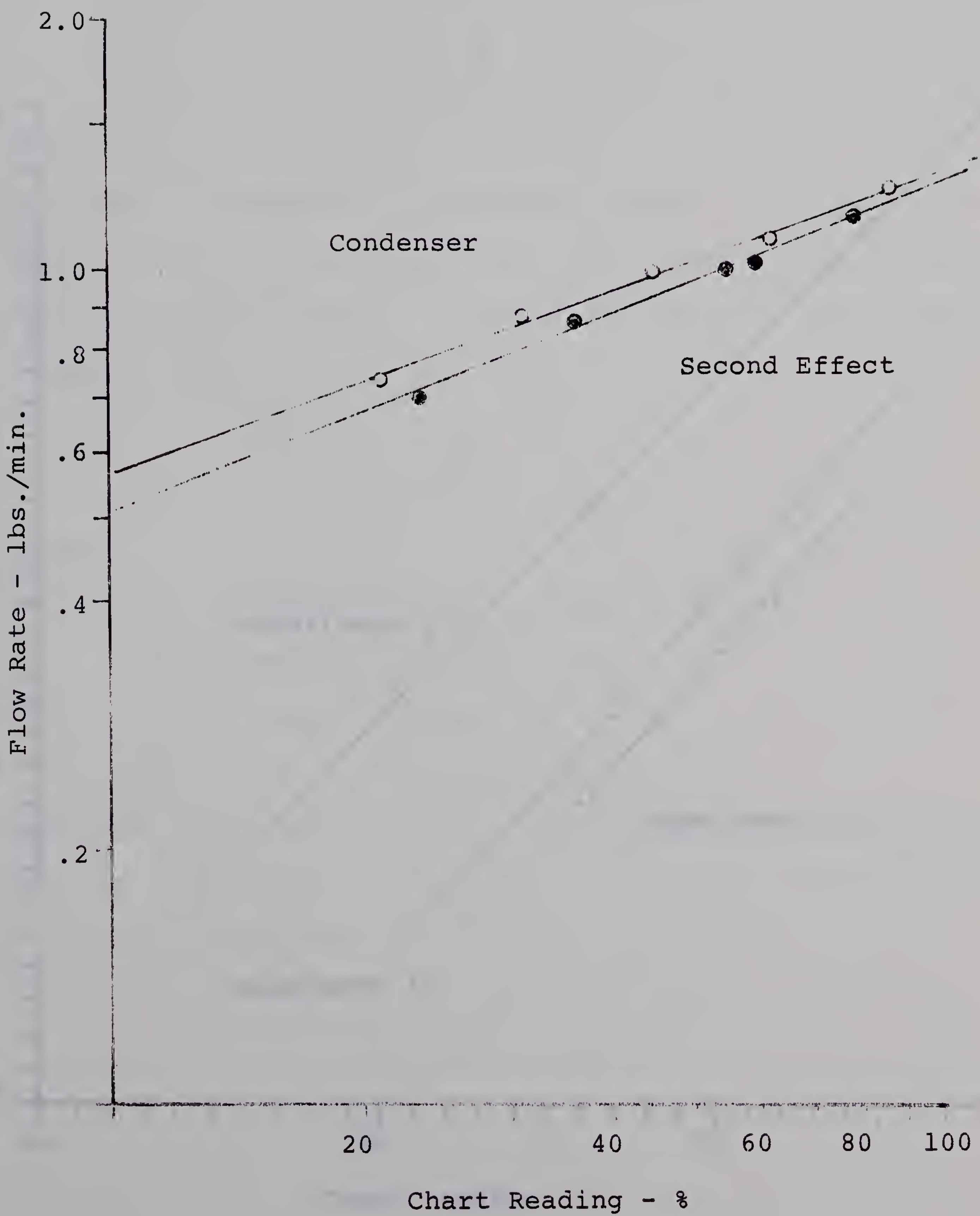
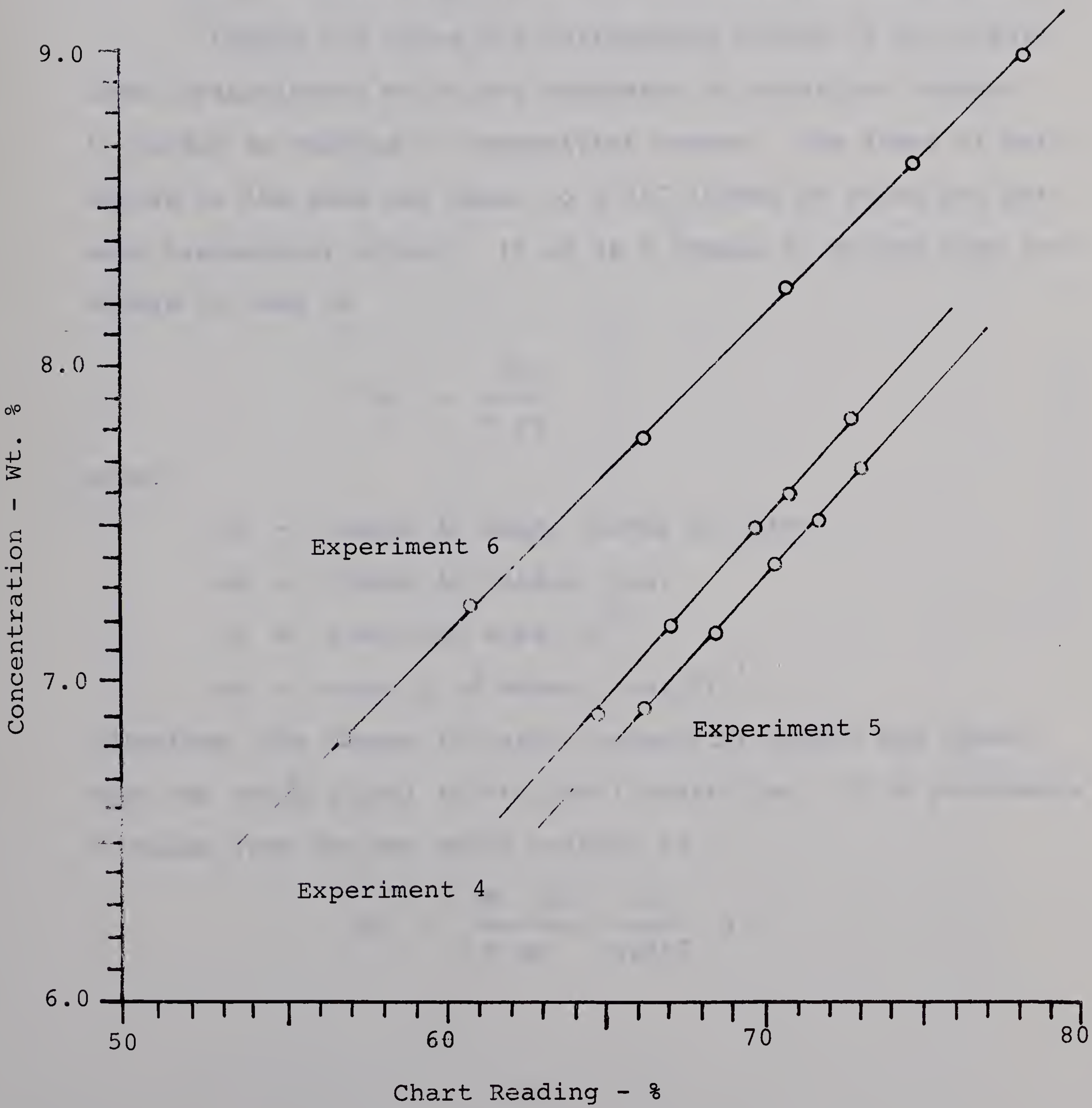


FIGURE 4-8

CALIBRATION CURVES

SECOND EFFECT CONCENTRATION



where

$\bar{C}_2$ = set point concentration, wt. fraction

C_2 = concentration, wt. fraction

Ec_2 = error signal to the concentration controller, %

Figure 4-9 shows the calibration curves of the liquid level transmitters which are necessary to translate changes in holdup to changes in transmitter output. The slope of both curves is the same and equal to 0.257 inches of water per percent transmitter output. If ΔW is a change in holdup then the change in head is

$$\Delta h = \frac{\Delta W}{A \rho w}$$

where

Δh = change in head, inches of water

ΔW = change in holdup, lbs.

A = x-section area, ft^2

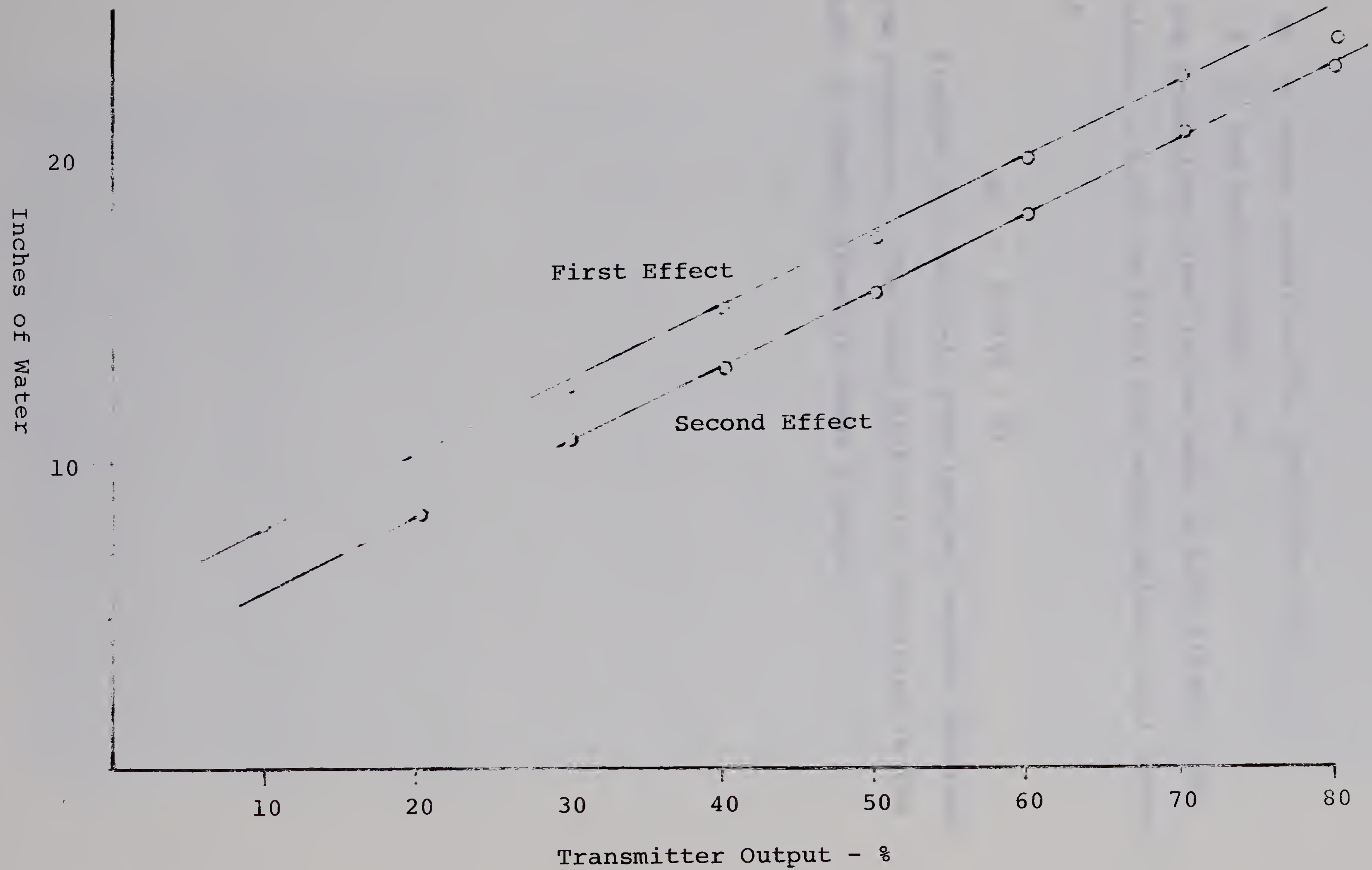
ρw = density of water, lbs./$ft.^3$

Therefore, the change in level transmitter output and therefore the error signal to the level controller, if ΔW represents a change from the set point holdup, is

$$EL = \frac{(W - \bar{W})}{A \rho w} \cdot \frac{12}{0.257} \ \%$$

FIGURE 4-9

CONCENTRATION OF LIQUID LEVEL TRANSMITTERS



where

EL = error signal to the controller, %

$\overline{W}$ = set point holdup, lbs.

Since the x-sectional area is the same in both effects, the error signal to both the first and second effect level controllers is

$$EL = 2.05(W - \overline{W})$$

Figures 4-10 and 4-11 show typical records obtained from the evaporator. The noise difficulty discussed in the main body is clearly shown in these figures.

FIGURE 4-10

TYPICAL RECORDS

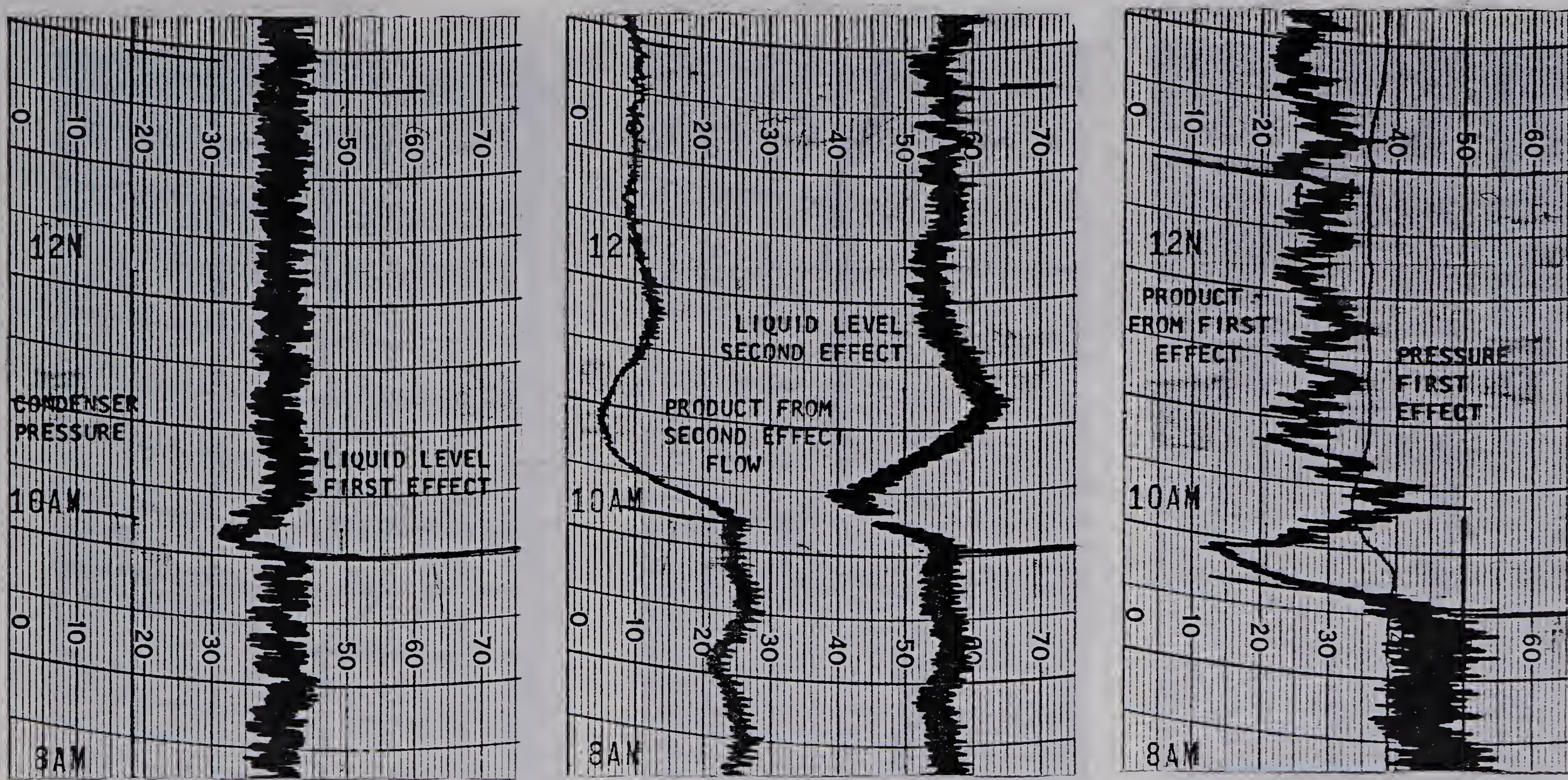
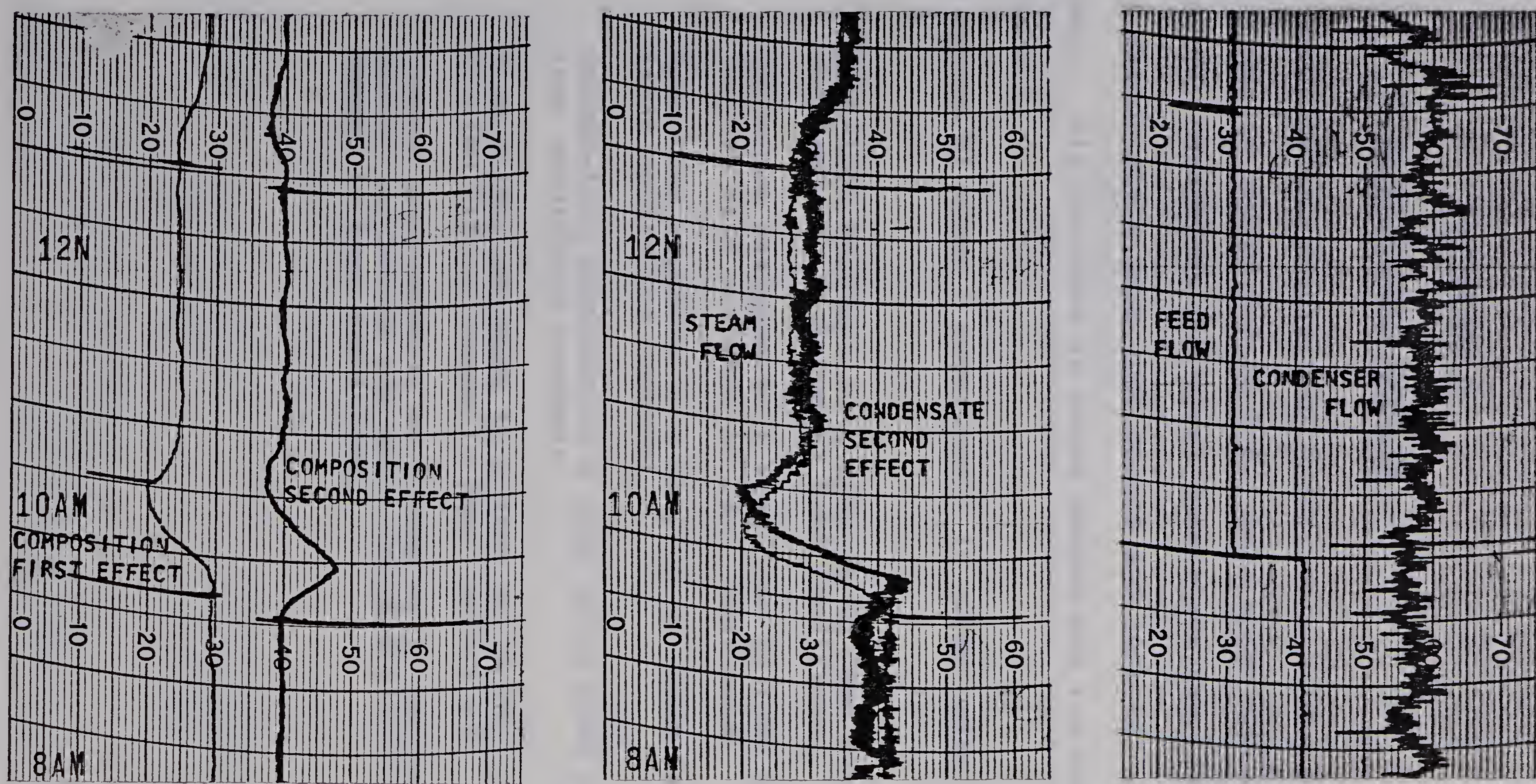


FIGURE 4-11

TYPICAL RECORDS



APPENDIX 5

EXPERIMENTAL RESULTS

The experimental results for experiments 1 to 6 inclusive are given in Tables 5-1 to 5-6. Data under the subheadings, Initial Conditions and Final Conditions are the experimental steady state data just before and just after each experiment. All the data in these tables are the unadjusted raw data.

The nature of these 6 experiments is given below.

Exp.	
1	Open-loop response to a step up in feed rate coupled with a change in feed conditions.
2	Open-loop response to a step down in feed rate coupled with a change in feed conditions.
3	Open-loop response to a step up in steam rate, steam conditions constant.
4	Closed-loop response to a step up in feed rate, feed conditions constant.
5	Closed-loop response to a step up in feed rate coupled with a change in feed conditions.
6	Closed-loop response to a step up in concentration controller set point coupled with a change in feed conditions.

TABLE 5-1

EXPERIMENTAL DATA FOR EXPERIMENT 1

Initial Conditions

F = 2.95 lbs./min.	B_1 = 1.92 lbs./min.	B_2 = .91 lbs./min.
Cf = 3.12%	C_1 = 4.79%	C_2 = 10.12%
T steam = 285°F	Ts_1 = 214°F	T_1 = 195.0°F
Tf = 99°F	T_2 = 150°F	SI = 1.31

Transient Data

Time mins.	Prod. 1st lbs./min.	Prod. 2nd lbs./min.	Conc. 1st %	Conc. 2nd %
0	1.92	.91	4.79	10.12
5	2.25	.99	4.66	10.01
10	2.53	1.26	4.51	9.56
15	2.67	1.62		
20	2.71	1.87	4.48	8.60
30	2.65	2.02	4.30	7.85
40	2.55	1.58	4.25	7.43
50	2.50	1.37	4.19	7.19
60	2.53	1.41	4.18	7.09
70	2.54	1.54	4.15	6.93
80	2.55	1.59		
90	2.54	1.60	4.20	6.93
100	2.53	1.58	4.18	6.89
110	2.53	1.55		
120	2.53	1.56	4.20	6.91
130	2.53	1.56		
150	2.53	1.55	4.20	6.88
160	2.53	1.55	4.20	6.87
170	2.53	1.55		
180	2.53	1.55	4.22	6.84

Final Conditions

F = 3.49 lbs./min.	B_1 = 2.53 lbs./min.	B_2 = 1.55 lbs./min.
Cf = 3.04%	C_1 = 4.20%	C_2 = 6.84%
T steam = 285°F	Ts_1 = 211.°F	T_1 = 192.2°F
Tf = 95.5°F	T_2 = 150.°F	SI = 1.31

Controller Settings

KL_1 = 80%	TL_1 = 6.0 min.
KL_2 = 80%	TL_2 = 6.0 min.

TABLE 5-2

EXPERIMENTAL DATA FOR EXPERIMENT 2

Initial Conditions

F = 3.8 lbs./min.	B_1 = 2.80 lbs./min.	B_2 = 1.85 lbs./min.
Cf = 3.10%	C_1 = 4.21%	C_2 = 6.48%
T steam = 255°F	Ts_1 = 214.°F	T_1 = 190.5°F
Tf = 93.°F	T_2 = 150.°F	S_1 = 1.36 lbs./min.

Transient Data

Time mins.	Prod. 1st. lbs./min.	Prod. 2nd. lbs./min.	Conc. 1st. %	Conc. 2nd. %
0	2.80	1.84	4.21	6.48
5	2.68		4.30	6.51
10	2.50	1.75	4.40	6.64
15	2.37	1.56	4.42	6.80
20	2.29	1.25	4.50	7.25
30	2.26	1.05	4.51	7.50
40	2.32	1.12	4.52	7.62
50	2.41	1.32	4.55	7.67
60	2.44	1.53		
70	2.42	1.59	4.55	7.68
80	2.41	1.44		
90	2.40	1.36	4.55	7.70
100	2.40	1.39	4.55	7.72
110	2.40	1.43		7.73
120	2.40	1.45	4.55	7.74
130	2.40	1.46		
140	2.40	1.45	4.55	7.75
150	2.40	1.43		
160	2.40	1.43	4.55	7.75
170	2.40	1.43		
180	2.40	1.43	4.55	7.75

Final Conditions

F = 3.40 lbs./min.	B_1 = 2.40 lbs./min.	B_2 = 1.43 lbs./min.
Cf = 3.22%	C_1 = 4.55%	C_2 = 7.75%
T steam = 255.°F	Ts_1 = 214.°F	T_1 = 191.0°F
Tf = 191.0°F	T_2 = 83°F	S_1 = 1.36 lbs./min.

Controller Settings

KL_1 = 80%	TL_1 = 8.5 min.
KL_2 = 160.%	TL_2 = 6.0 min.

TABLE 5-3

EXPERIMENTAL DATA FOR EXPERIMENT 3

Initial Conditions

F = 3.31 lbs./min. B_1 = 2.23 lbs./min. B_2 = 1.16 lbs./min.
Cf = 2.78% C_1 = 4.09% C_2 = 7.92%
T steam = 255°F Ts_1 = 223°F T_2 = 179°F
Tf = 90.°F T_1 = 150.°F S_1 = 1.42 lbs./min.

Transient Data

Time mins.	Prod. 1st. lbs./min.	Prod. 2nd. lbs./min.	Conc. 1st. %	Conc. 2nd. %
0	2.23	1.16	4.09	7.92
5	2.20	1.13		
10	2.15	1.07	4.15	8.12
20	2.10	.97	4.20	9.45
30	2.11	.86	4.25	8.78
40	2.14	.825	4.25	8.98
50	2.14	.88	4.26	9.08
60	2.13	.965	4.27	9.23
70	2.13	1.00	4.28	9.30
80	2.13	1.00	4.30	9.39
90	2.13	.98	4.30	9.45
100	2.13	.965	4.30	9.45
110	2.13	.96	4.30	9.47
120	2.13	.96	4.30	9.48
130	2.13	.96	4.30	9.49
140	2.13	.96	4.30	9.50
150	2.13	.96	4.30	9.50
160	2.13	.96	4.30	9.50
170	2.13	.96	4.30	9.50
180	2.13	.96	4.31	9.50

Final Conditions

F = 3.31 lbs./min. B_1 = 2.13 lbs./min. B_2 = .95 lbs./min.
Cf = 2.78% C_1 = 4.30% C_2 = 9.50%
T steam = 255°F Ts_1 = 227°F T_2 = 203°F
Tf = 90°F T_1 = 150°F S_1 = 1.54 lbs./min.

Controller Settings

KL_1 = 80% TL_1 = 7.0 min.
KL_2 = 160% TL_2 = 6.0 min.

TABLE 5-4

EXPERIMENTAL DATA FOR EXPERIMENT 4

Initial Conditions

F = 2.43 lbs./min.
Cf = 3.02%
T steam = 283^{o}F
Tf = 88.5^{o}F

B_1 = 1.69 lbs./min.
C_1 = 4.34%
Ts_1 = 201^{o}F
T_2 = 149.5^{o}F

B_2 = .98 lbs./min.
C_2 = 7.51%
T_1 = 184^{o}F
Si = .94

Transient Data

Time mins.	Prod. 1st. lbs./min.	Prod. 2nd. lbs./min.	Steam lbs./min.	Conc. 1st. %	Conc. 2nd. %
0	1.69	.98	.94	4.34	7.51
5	1.895	.98	.99		7.40
10	2.23	1.10	1.025	4.20	7.21
15	2.31	1.26	1.09		6.98
20	2.30	1.66	1.16	4.19	6.88
30	2.07	1.75	1.23	4.26	6.99
40	1.85	1.09	1.22	4.35	7.43
50	1.90	.78	1.18	4.41	7.77
60	2.00	.795	1.14	4.36	7.72
70	2.08	.98	1.12	4.31	7.61
80	2.07	1.25	1.12	4.28	7.50
90	2.05	1.41	1.13	4.30	7.47
100	2.02	1.39	1.14	4.31	7.47
110	2.02	1.20	1.15	4.32	7.49
120	2.03	1.06	1.16	4.32	7.50
130	2.04	1.05	1.16	4.32	7.51
140	2.05	1.10	1.16	4.32	7.51
150	2.05	1.14	1.16	4.32	7.51
160	2.05	1.16	1.16	4.32	7.51
170	2.05	1.17	1.16	4.32	7.51
180	2.05	1.18	1.16	4.32	7.51

Final Conditions

F = 2.93 lbs./min.
Cf = 3.02%
T steam = 283^{o}F
Tf = 93^{o}F

B_1 = 2.05 lbs/min.
C_1 = 4.32%
Ts_1 = 211^{o}F
T_2 = 49.5^{o}F

B_2 = 1.18 lbs./min.
C_2 = 7.51%
T_1 = 190^{o}F
Si = 1.16

Controller Settings

KL_1 = 80% TL_1 = 6. min.
KL_2 = 175% TL_2 = 6. min.
Kc_2 = 130% TL_2 = 7. min. Tdc_2 = 5 min.

TABLE 5-5

EXPERIMENTAL DATA FOR EXPERIMENT 5

Initial Conditions

F = 2.93 lbs./min. B_1 = 2.05 lbs./min. B_2 = 1.225 lbs./min.
Cf = 3.19% C_1 = 4.56% C_2 = 7.62%
T steam = 282.5°F Ts_1 = 207.5°F T_1 = 189.°F
Tf = 90.5°F T_2 = 150.0°F Si = 1.14 lbs./min.

Transient Data

Time mins.	Prod. 1st. lbs./min.	Prod. 2nd. lbs./min.	Steam lbs./min.	Conc. 1st. %	Conc. 2nd. %
0	2.05	1.225	1.135	4.56	7.62
5	2.30	1.275	1.15		7.59
10	2.54	1.41	1.20	4.35	7.34
15	2.61	1.62	1.265		7.15
20	2.60	1.73	1.33	4.18	6.96
30	2.46	1.72	1.405	4.25	6.92
40	2.24	1.43	1.42	4.30	7.27
50	2.23	1.07	1.40	4.33	7.64
60	2.31	1.01	1.37	4.31	7.745
70	2.38	1.10	1.365	4.25	7.68
80	2.40	1.26	1.37	4.30	7.63
90	2.38	1.45	1.38	4.30	7.56
100	2.35	1.47	1.38	4.29	7.565
110	2.35	1.38	1.38	4.29	7.59
120	2.36	1.32	1.375	4.30	7.62
130	2.37	1.27	1.38	4.30	7.63
140	2.38	1.28	1.38	4.30	7.62
150	2.37	1.30	1.38	4.30	7.62
160	2.36	1.31	1.38	4.30	7.62
170	2.35	1.32	1.38	4.30	7.62
180	2.35	1.33	1.38	4.30	7.62

Final Conditions

F = 3.40 lbs./min. B_1 = 2.35 lbs./min. B_2 = 1.33 lbs./min.
Cf = 3.0% C_1 = 4.30% C_2 = 7.62%
T steam = 282.5°F Ts_1 = 213.5°F T_1 = 194°F
Tf = 90.5°F T_2 = 150.0°F Si = 1.38 lbs./min.

Controller Settings

KL_1 = 80% TL_1 = 6 min.

KL_2 = 175% TL_2 = 6 min.

Kc_2 = 130% Tc_2 = 7 min. Tdc_2 = 5 min.

TABLE 5-6

EXPERIMENTAL DATA FOR EXPERIMENT 6

Initial Conditions

F = 3.40 lbs./min.	B_1 = 2.41 lbs./min.	B_2 = 1.42 lbs./min.
Cf = 3.16%	C_1 = 4.46%	C_2 = 7.57%
T steam = 279.5^{o}F	Ts_1 = 214^{o}F	T_1 = 182.5^{o}F
Tf = 87.5^{o}F	T_2 = 150.0	S_1 = 1.32

Transient Data

Time mins.	Prod. lst. lbs./min.	Prod. 2nd. lbs./min.	Steam lbs./min.	Conc. lst. %	Conc. 2nd. %
0	2.41	1.42	1.32	4.46	7.57
5	2.33	1.40	1.50	4.46	7.64
10	2.26	1.30	1.53	4.46	7.94
15	2.19	1.16	1.54	4.45	8.19
25	2.14	.89	1.53	4.44	8.64
35	2.17	.92	1.505	4.45	9.01
45	2.26	.86	1.49	4.41	9.06
55	2.32	1.04	1.48	4.40	8.99
65	2.29	1.29	1.47	4.38	8.89
80	2.27	1.32	1.48	4.35	8.74
90	2.25	1.145	1.49	4.36	8.69
100	2.24	1.05	1.50	4.37	8.73
110	2.23	1.05	1.49	4.38	8.75
120	2.23	1.10	1.48	4.38	8.80
130	2.23	1.13	1.48	4.38	8.81
140	2.24	1.14	1.48		8.80
150	2.24	1.13	1.48		8.79
160	2.24	1.125	1.48		8.76
170	2.24	1.125	1.48		8.75
180	2.24	1.125	1.48	4.38	8.74

Final Conditions

F = 3.40 lbs./min.	B_1 = 2.24 lbs./min.	B_2 = 1.125 lbs./min.
Cf = 2.90%	C_1 = 4.38%	C_2 = 8.74%
T steam = 279.5^{o}F	Ts_1 = 218.5^{o}F	T_1 = 187^{o}F
Tf = 87.5^{o}F	T_2 = 150.^{o}F	S_1 = 1.49 lbs./min.

Controller Settings

KL_1 = 80%	TL_1 = 6.0 min.	
KL_2 = 160%	TL_2 = 6.0 min.	
Kc_2 = 120%	Tc_2 = 7.0 min.	Tdc_2 = 5.0 min.

APPENDIX 6

DATA ADJUSTMENT AND STEADY STATE PROGRAMS

The method of adjusting the steady state data to satisfy material balances has been outlined in the main body of the thesis. The computation procedure is; read in the experimental initial data through a main line program and call the data adjustment sub-routine which performs the above-mentioned data adjustments and calculate heat transfer coefficients and heat losses from the adjusted data. Control is returned to the main line program and the experimental data for the final conditions are read in. The above procedure is repeated for this data and then average heat transfer coefficients and heat losses are calculated. Also at this time various perturbations to the system such as step change in feed or feed concentration are made compatible with the adjusted data.

After the above computations, the main line program calls the steady state program which calculates the initial conditions in the fashion described in Chapter VII of this thesis.

These two sub-routines are shown in the following pages of this appendix.

```
      SUBROUTINE DATA(L)
C
C    THIS SUBROUTINE ADJUSTS THE DATA TO SATISFY THE
C     MAT. BALANCES AND CALCULATES THE HT COEFFS. AND
C     HEAT LOSSES
C
      REAL KL1,KL2,KC2
      COMMON F,B1,B2,SI,O1,O2,B1O,B2O,SIO,CF,C1,C2,C2R,V1,V2,W1
      COMMON W2,W1R,W2R,DENS1,DENS2,TS1,TF,T1,T2,UA1,UA2,HL2,HF
      COMMON H1,H2,HSI,STEPF,STEPCF,STEPTF,STEPSI,STEPC2,Y(15)
      COMMON D(15),E(20),C(20),SIGL1O,OL,KL1,KL2,KC2,TL1,TL2
      COMMON TC2,TDC2,TI(100),G1(100),G2(100),NC,HL1,HL3,SIGSIO
      COMMON SDENS,KMM,EW1,EW2
      DIMENSION STEAM(2),TEMPF(2)
      DIMENSION HTC1(2),HTL2(2),HTC2(2),FEED(2),FDC(2),B2C(2)
      DIMENSION HTL3(2)
  701 SUG1=F*CF
      SUG2=B1*C1
      SUG3=B2*C2
      SUGA=(SUG1+SUG2+SUG3)/3.
      IF(ABS(1.-SUG1/SUGA).GT.0.0005)GO TO 703
      IF(ABS(1.-SUG2/SUGA).GT.0.0005)GO TO 703
      IF(ABS(1.-SUG3/SUGA).GT.0.0005)GO TO 703
      GO TO 704
  703 F=F+.7*(SUGA-SUG1)/CF
      CF=CF+.3*(SUGA-SUG1)/F
      B1=B1+.7*(SUGA-SUG2)/C1
      C1=C1+.3*(SUGA-SUG2)/B1
      B2=B2+.7*(SUGA-SUG3)/C2
      C2=C2+.3*(SUGA-SUG3)/B2
      GO TO 701
  704 H1=T1*(1.-.454*C1)-32.1+6.0*C1
      H2=T2*(1.-.454*C2)-32.1+6.0*C2
      HVAP=1098.-.6*T1
      HO2=1066.1+.4*T2
      O1=F-B1
      O2=B1-B2
      Q2=O1*HVAP
      HL3=(Q2+B1*H1-B2*H2-O2*HO2)/1.25
      HL2=.25*HL3
      UA2=(Q2-HL2)/(T1-T2)
      HO1=1066.1+.4*T1
      HF=TF*(1.-.454*CF)-32.1+6.0*CF
      Q1=B1*H1+O1*HO1-F*HF
      UA1=Q1/(TS1-T1)
      HLC1=TS1-32.0
  705 SI=Q1/(HSI-HLC1)
      HTC1(L)=UA1
      HTC2(L)=UA2
      HTL2(L)=HL2
      HTL3(L)=HL3
      FEED(L)=F
```

```
      SUBROUTINE DATA(L)
C
C     THIS SUBROUTINE ADJUSTS THE DATA TO SATISFY THE
C     MAT. BALANCES AND CALCULATES THE HT COEFFS. AND
C     HEAT LOSSES
C
      REAL KL1,KL2,KC2
      COMMON F,B1,B2,S1,O1,O2,B1O,B2O,S1O,CF,C1,C2,C2R,V1,V2,W1
      COMMON W2,W1R,W2R,DENS1,DENS2,TS1,TF,T1,T2,UA1,UA2,HL2,HF
      COMMON H1,H2,HS1,STEPF,STEPCF,STEPTF,STEPS1,STEPC2,Y(15)
      COMMON D(15),E(20),C(20),SIGL1O,OL,KL1,KL2,KC2,TL1,TL2
      COMMON TC2,TDC2,TI(100),G1(100),G2(100),NC,HL1,HL3,SIGS1O
      COMMON SDENS,KMM,EW1,EW2
      DIMENSION STEAM(2),TEMPF(2)
      DIMENSION HTC1(2),HTL2(2),HTC2(2),FEED(2),FDC(2),B2C(2)
      DIMENSION HTL3(2)
  701 SUG1=F*CF
      SUG2=B1*C1
      SUG3=B2*C2
      SUGA=(SUG1+SUG2+SUG3)/3.
      IF(ABS(1.-SUG1/SUGA).GT.0.0005)GO TO 703
      IF(ABS(1.-SUG2/SUGA).GT.0.0005)GO TO 703
      IF(ABS(1.-SUG3/SUGA).GT.0.0005)GO TO 703
      GO TO 704
  703 F=F+.7*(SUGA-SUG1)/CF
      CF=CF+.3*(SUGA-SUG1)/F
      B1=B1+.7*(SUGA-SUG2)/C1
      C1=C1+.3*(SUGA-SUG2)/B1
      B2=B2+.7*(SUGA-SUG3)/C2
      C2=C2+.3*(SUGA-SUG3)/B2
      GO TO 701
  704 H1=T1*(1.-.454*C1)-32.1+6.0*C1
      H2=T2*(1.-.454*C2)-32.1+6.0*C2
      HVAP=1098.-.6*T1
      HO2=1066.1+.4*T2
      O1=F-B1
      O2=B1-B2
      Q2=O1*HVAP
      HL3=(Q2+B1*H1-B2*H2-O2*HO2)/1.25
      HL2=.25*HL3
      UA2=(Q2-HL2)/(T1-T2)
      HO1=1066.1+.4*T1
      HF=TF*(1.-.454*CF)-32.1+6.0*CF
      Q1=B1*H1+O1*HO1-F*HF
      UA1=Q1/(TS1-T1)
      HLC1=TS1-32.0
  705 S1=Q1/(HS1-HLC1)
      HTC1(L)=UA1
      HTC2(L)=UA2
      HTL2(L)=HL2
      HTL3(L)=HL3
      FEED(L)=F
```

```
      FDC(L)=CF
      B2C(L)=C2
      TEMPF(L)=TF
      STEAM(L)=SI
      IF(L.NE.2)GO TO 725
      HL2=(HTL2(2)+HTL2(1))/2.
      HL3=(HTL3(2)+HTL3(1))/2.
      UA1=(HTC1(2)+HTC1(1))/2.
      UA2=(HTC2(2)+HTC2(1))/2.
      TF=TEMPF(1)
      IF(ABS(STEPTF).LT..9)TF=(TF+TEMPF(2))/2.
      CF=FDC(1)
      IF(ABS(STEPCF).LT..0005)CF=(CF+FDC(2))/2.
      IF(ABS(STEPCF).GT..0005)STEPCF=FDC(2)-FDC(1)
      IF(OL)708,708,709
  708 C2=B2C(1)
      STEPC2=B2C(2)-B2C(1)
      GO TO 710
  709 IF(ABS(STEPC2).GT..002)GO TO 708
      C2=(B2C(2)+B2C(1))/2.
  710 F=FEED(1)
      IF(ABS(STEPF).LT.0.1)GO TO 712
      STEPF=FEED(2)-FEED(1)
      GO TO 713
  712 F=(F+FEED(2))/2.
  713 IF(ABS(STEPSI).GT.0.1)STEPSI=STEAM(2)-STEAM(1)
  725 CONTINUE
      RETURN
      END
```

```
      FDC(L)=CF
      B2C(L)=C2
      TEMPF(L)=TF
      STEAM(L)=SI
      IF(L.NE.2)GO TO 725
      HL2=(HTL2(2)+HTL2(1))/2.
      HL3=(HTL3(2)+HTL3(1))/2.
      UA1=(HTC1(2)+HTC1(1))/2.
      UA2=(HTC2(2)+HTC2(1))/2.
      TF=TEMPF(1)
      IF(ABS(STEPTF).LT..9)TF=(TF+TEMPF(2))/2.
      CF=FDC(1)
      IF(ABS(STEPCF).LT..0005)CF=(CF+FDC(2))/2.
      IF(ABS(STEPCF).GT..0005)STEPCF=FDC(2)-FDC(1)
      IF(OL)708,708,709
  708 C2=B2C(1)
      STEPC2=B2C(2)-B2C(1)
      GO TO 710
  709 IF(ABS(STEPC2).GT..002)GO TO 708
      C2=(B2C(2)+B2C(1))/2.
  710 F=FEED(1)
      IF(ABS(STEPF).LT.0.1)GO TO 712
      STEPF=FEED(2)-FEED(1)
      GO TO 713
  712 F=(F+FEED(2))/2.
  713 IF(ABS(STEPSI).GT.0.1)STEPSI=STEAM(2)-STEAM(1)
  725 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE STEADY
C
C     SUBROUTINE TO CALCULATE INITIAL CONDITIONS
C
      REAL KL1,KL2,KC2
      COMMON F,B1,B2,SI,O1,O2,B1O,B2O,SIO,CF,C1,C2,C2R,V1,V2,W1
      COMMON W2,W1R,W2R,DENS1,DENS2,TS1,TF,T1,T2,UA1,UA2,HL2,HF
      COMMON H1,H2,HSI,STEPF,STEPCF,STEPTF,STEPSI,STEPC2,Y(15)
      COMMON D(15),E(20),C(20),SIGL1O,OL,KL1,KL2,KC2,TL1,TL2
      COMMON TC2,TDC2,TI(100),G1(100),G2(100),NC,HL1,HL3,SIGSIO
      COMMON SDENS,KMM,EW1,EW2
      DIMENSION FI(3),FS(3)
      HO2=1066.1+.4*T2
      H2=T2*(1.-.454*C2)+6.*C2-32.1
      LL=1
C   CALC. PROD. RATE FROM OVERALL MAT. BAL.
      B2=F*CF/C2
      N1=1
C   ESTIMATE VAP. RATE FROM FIRST EFFECT
      O1=(F-B2)/2.
 4    JJ=1
C   COMPLETE MAT. BAL.
 5    B1=F-O1
      C1=F*CF/B1
      O2=B1-B2
      N2=1
C   ESTIMATE TEMP. OF FIRST EFFECT
      T1=195.
  9   CONTINUE
 10   H1=T1*(1.-.454*C1)-32.1+6.*C1
      Q2=O2*HO2-B1*H1+B2*H2+HL3
      T1T=T2+Q2/UA2
      DIF1=ABS(T1T-T1)
      IF(DIF1-0.001)70,70,13
 13   T1=(T1+T1T)/2.
      N2=N2+1
      IF(N2.GE.400)GO TO 65
      GO TO 9
 65   WRITE(6,66)
 66   FORMAT(1HJ,27H CONVERGENCE FAILURE IN T1  )
      GO TO 167
 70   CONTINUE
C   CHECK AND/OR ALTER O1
      HVAP=1098.-.6*T1
      SC=(Q2+HL2)/HVAP
      FS(JJ)=SC-O1
      DIF2=ABS(FS(JJ))
      IF(DIF2-0.00001)86,86,80
 80   IF(JJ.GE.2)GO TO 81
      O1I=O1
      O1=O1*1.000001
      JJ=2
```

```
      SUBROUTINE STEADY
C
C     SUBROUTINE TO CALCULATE INITIAL CONDITIONS
C
      REAL KL1,KL2,KC2
      COMMON F,B1,B2,S1,O1,O2,B10,B20,S10,CF,C1,C2,C2R,V1,V2,W1
      COMMON W2,W1R,W2R,DENS1,DENS2,TS1,TF,T1,T2,UA1,UA2,HL2,HF
      COMMON H1,H2,HS1,STEPF,STEPCF,STEPTF,STEPS1,STEPC2,Y(15)
      COMMON D(15),E(20),C(20),SIGL10,OL,KL1,KL2,KC2,TL1,TL2
      COMMON TC2,TDC2,TI(100),G1(100),G2(100),NC,HL1,HL3,SIGS10
      COMMON SDENS,KMM,EW1,EW2
      DIMENSION FI(3),FS(3)
      HO2=1066.1+.4*T2
      H2=T2*(1.-.454*C2)+6.*C2-32.1
      LL=1
C     CALC. PROD. RATE FROM OVERALL MAT. BAL.
      B2=F*CF/C2
      N1=1
C     ESTIMATE VAP. RATE FROM FIRST EFFECT
      O1=(F-B2)/2.
    4 JJ=1
C     COMPLETE MAT. BAL.
    5 B1=F-O1
      C1=F*CF/B1
      O2=B1-B2
      N2=1
C     ESTIMATE TEMP. OF FIRST EFFECT
      T1=195.
    9 CONTINUE
   10 H1=T1*(1.-.454*C1)-32.1+6.*C1
      Q2=O2*HO2-B1*H1+B2*H2+HL3
      T1T=T2+Q2/UA2
      DIF1=ABS(T1T-T1)
      IF(DIF1-0.001)70,70,13
   13 T1=(T1+T1T)/2.
      N2=N2+1
      IF(N2.GE.400)GO TO 65
      GO TO 9
   65 WRITE(6,66)
   66 FORMAT(1H1,27H CONVERGENCE FAILURE IN T1  )
      GO TO 167
   70 CONTINUE
C     CHECK AND/OR ALTER O1
      HVAP=1098.-.6*T1
      SC=(Q2+HL2)/HVAP
      FS(JJ)=SC-O1
      DIF2=ABS(FS(JJ))
      IF(DIF2-0.0001)86,86,80
   80 IF(JJ.GE.2)GO TO 81
      O11=O1
      O1=O1*1.000001
      JJ=2
```

```
      GO TO 5
81    O1=O1I-FS(1)*O1I*0.000001/(FS(2)-FS(1))
      N1=N1+1
      IF(N1.GE.200)GO TO 84
      GO TO 4
84    WRITE(6,85)
85    FORMAT(1HJ,27H  CONVERGENCE FAILURE IN O1  )
      GO TO 167
86    CONTINUE
      IF(LL.GE.2)GO TO 88
      LL=3
      GO TO 4
88    CONTINUE
C   CALC. INITIAL CONDITIONS
      DENS1=(1.+.41*C1)*(64.57-.022*T1)
      DENS2=(1.+.41*C2)*(64.57-.022*T2)
      HO1=1066.1+.4*T1
      HF=TF*(1.-.454*CF)-32.1+6.0*CF
      Q1=F*(H1-HF)+O1*(HO1-H1)
      TS1=Q1/UA1+T1
      SI=Q1/(HSI+32.0-1.01*TS1)
      W1R=DENS1*.610
      W2R=DENS2*.425
      Y(2)=W1R
      Y(3)=H1*W1R
      Y(4)=C1*W1R
      Y(5)=W2R
      Y(6)=C2*W2R
      Y(7)=0.0
      Y(8)=0.0
      Y(9)=0.0
      DO 91 JP=1,20
      C(JP)=C1
91    E(JP)=H1
      B1O=B1
      B2O=B2
      SIO=SI
      C2R=C2
      B1NOR=B1O/1.33
      SIGL1O=B1NOR**2.0790021
      SINOR=SI/(0.680*SDENS)
      SIGSIO=SINOR**2.1978022
167   CONTINUE
      RETURN
      END
```

```
      GO TO 5
   81 OI=OII-FS(1)*OII*0.000001/(FS(2)-FS(1))
      NI=NI+1
      IF(NI.GE.200)GO TO 84
      GO TO 4
   84 WRITE(6,85)
   85 FORMAT(1H1,27H   CONVERGENCE FAILURE IN OI )
      GO TO 167
   86 CONTINUE
      IF(LL.GE.2)GO TO 88
      LL=3
      GO TO 4
   88 CONTINUE
C   CALC. INITIAL CONDITIONS
      DENS1=(1.+.41*C1)*(64.57-.022*T1)
      DENS2=(1.+.41*C2)*(64.57-.022*T2)
      HO1=1066.1+.4*T1
      HF=TF*(1.-.454*CF)-32.1+6.0*CF
      Q1=F*(H1-HF)+OI*(HO1-H1)
      TS1=Q1/UA1+T1
      S1=Q1/(HS1+32.0-1.01*TS1)
      W1R=DENS1*.610
      W2R=DENS2*.425
      Y(2)=W1R
      Y(3)=H1*W1R
      Y(4)=C1*W1R
      Y(5)=W2R
      Y(6)=C2*W2R
      Y(7)=0.0
      Y(8)=0.0
      Y(9)=0.0
      DO 91 JP=1,20
      C(JP)=C1
   91 E(JP)=H1
      B10=B1
      B20=B2
      S10=S1
      C2R=C2
      BINOR=B10/1.33
      SIGL10=BINOR**2.079002
      SINOR=S1/(0.680*SDENS)
      SIGS10=SINOR**2.197802
  167 CONTINUE
      RETURN
      END
```

APPENDIX 7

COMPUTER PROGRAMS FOR SOLVING THE MODEL

The computer program for solution of the model consists of a main line program, a Runge-Kutta-Gill integration sub-routine, a sub-routine to calculate the derivatives for integration, a sub-routine to control the print out and a sub-routine to apply the pertinent perturbations to the system. All of these sub-routines are relatively straight-forward and thus require no further clarification.

It can be seen that the perturbating sub-routine is called from the integration routine 4 mins. (real time) after the solution has been started. This was done simply to be able to check if the initial conditions produced by the steady state routine were truely steady state.

For experiments 1, 2, 5 and 6 in which there was a change in feed tanks at the start, it was determined experimentally that approximately three minutes were required for any changes in feed concentration and/or feed temperature to reach the process. Therefore, for the above experiments, these perturbations were imposed on the system 3 minutes after the initial perturbation.

```
C
C
C       SIMULATION OF A TWO STAGE CONCENTRATING EVAPORATOR
C
C                             INPUT DATA
C
C    KL1,KL2,KC2=PROPORTIONAL BANDS OF THE INDICATED CONTROLLERS
C    TL1,TL2,TC2=INTEGRAL TIMES OF THE INDICATED CONTROLLERS
C    TDC2=DERIVATIVE TIME OF THE COMPOSITION CONTROLLER
C    F,CF,TF=FLOW, CONC., AND TEMP., OF THE FEED AT STEADY STATE
C    STEPF,STEPCF,STEPTF,STEPSI,STEPC2=PERTURBATIONS IN THE
C     INDICATED PARAMETERS
C    H=INCREMENT SIZE IN THE INTEGRATION SUBROUTINE
C    END=DURATION OF EXPERIMENT
C    WRTE=TIME BETWEEN PRINTOUTS
C    OL=FLAG- EQUALS -1. FOR OPEN-LOOP TESTS AND +1. FOR CLOSED
C    B1,B2=BOTTOM PRODUCT FROM THE FIRST AND SECOND EFFECTS
C    O1,O2=OVERHEAD FROM THE FIRST AND SECOND EFFECTS
C    SI=STEAM TO THE FIRST EFFECT
C    C1,C2=CONCENTRATIONS OF FIRST AND SECOND EFFECTS
C    TS1,T1,T2=TEMPS OF THE STEAM,FIRST AND SECOND EFFECTS
C    SDENS=SQUARE ROOT OF SUPPLY STEAM DENSITY
C    HSI=ENTHALPY OF SUPPLY STEAM
C
      REAL KL1,KL2,KC2
      COMMON F,B1,B2,SI,O1,O2,B10,B20,SI0,CF,C1,C2,C2R,V1,V2,W1
      COMMON W2,W1R,W2R,DENS1,DENS2,TS1,TF,T1,T2,UA1,UA2,HL2,HF
      COMMON H1,H2,HSI,STEPF,STEPCF,STEPTF,STEPSI,STEPC2,Y(15)
      COMMON D(15),E(20),C(20),SIGL10,OL,KL1,KL2,KC2,TL1,TL2
      COMMON TC2,TDC2,TI(100),G1(100),G2(100),NC,HL1,HL3,SIGSI0
      COMMON SDENS,KMM,EW1,EW2
      DIMENSION AP(12),AQ(12)
      DO 708 KMM=1,10
      READ(5,17) H,END,WRTE
      READ(5,11)NRUN
      WRITE(6,33)
      WRITE(6,21)NRUN
      READ(5,12)(AP(I),I=1,12)
      READ(5,12) (AQ(I),I=1,12)
      WRITE(6,22)(AP(I),I=1,12)
      WRITE(6,34)(AQ(I),I=1,12)
      WRITE(6,23)
      READ(5,15)F,B1,B2,CF,C1,C2,TF,TS1,T1,T2,HSI
      WRITE(6,25)
      WRITE(6,26)F,B1,B2,CF,C1,C2,TF,TS1,T1,T2,HSI
      L=1
      CALL DATA(L)
      READ(5,15)F,B1,B2,CF,C1,C2,TF,TS1,T1,T2,HSI
      WRITE(6,27)
      WRITE(6,26)F,B1,B2,CF,C1,C2,TF,TS1,T1,T2,HSI
      READ(5,16)STEPF,STEPSI,STEPCF,STEPTF,STEPC2,OL
      L=2
```

```
C
C
C       SIMULATION OF A TWO STAGE CONCENTRATING EVAPORATOR
C
C                 INPUT DATA
C
C     KL1,KL2,KC2=PROPORTIONAL BANDS OF THE INDICATED CONTROLLERS
C     TL1,TL2,TC2=INTEGRAL TIMES OF THE INDICATED CONTROLLERS
C     TDC2=DERIVATIVE TIME OF THE COMPOSITION CONTROLLER
C     F,CF,TF=FLOW, CONC., AND TEMP., OF THE FEED AT STEADY STATE
C     STEPF,STEPCF,STEPTF,STEPS1,STEPC2=PERTURBATIONS IN THE
C      INDICATED PARAMETERS
C     H=INCREMENT SIZE IN THE INTEGRATION SUBROUTINE
C     END=DURATION OF EXPERIMENT
C     WRTE=TIME BETWEEN PRINTOUTS
C     OL=FLAG- EQUALS -1. FOR OPEN-LOOP TESTS AND +1. FOR CLOSED
C     B1,B2=BOTTOM PRODUCT FROM THE FIRST AND SECOND EFFECTS
C     O1,O2=OVERHEAD FROM THE FIRST AND SECOND EFFECTS
C     S1=STEAM TO THE FIRST EFFECT
C     C1,C2=CONCENTRATIONS OF FIRST AND SECOND EFFECTS
C     TS1,T1,T2=TEMPS OF THE STEAM,FIRST AND SECOND EFFECTS
C     SDENS=SQUARE ROOT OF SUPPLY STEAM DENSITY
C     HS1=ENTHALPY OF SUPPLY STEAM
C
      REAL KL1,KL2,KC2
      COMMON F,B1,B2,S1,O1,O2,B10,B20,S10,CF,C1,C2,C2R,V1,V2,W1
      COMMON W2,W1R,W2R,DENS1,DENS2,TS1,TF,T1,T2,UA1,UA2,HL2,HF
      COMMON H1,H2,HS1,STEPF,STEPCF,STEPTF,STEPS1,STEPC2,Y(15)
      COMMON D(15),E(20),C(20),SIGL10,OL,KL1,KL2,KC2,TL1,TL2
      COMMON TC2,TDC2,TI(100),G1(100),G2(100),NC,HL1,HL3,SIGS10
      COMMON SDENS,KMM,EW1,EW2
      DIMENSION AP(12),AQ(12)
      DO 708 KMM=1,10
      READ(5,17) H,END,WRTE
      READ(5,11)NRUN
      WRITE(6,33)
      WRITE(6,21)NRUN
      READ(5,12)(AP(I),I=1,12)
      READ(5,12) (AQ(I),I=1,12)
      WRITE(6,22)(AP(I),I=1,12)
      WRITE(6,34)(AQ(I),I=1,12)
      WRITE(6,23)
      READ(5,15)F,B1,B2,CF,C1,C2,TF,TS1,T1,T2,HS1
      WRITE(6,25)
      WRITE(6,26)F,B1,B2,CF,C1,C2,TF,TS1,T1,T2,HS1
      L=1
      CALL DATA(L)
      READ(5,15)F,B1,B2,CF,C1,C2,TF,TS1,T1,T2,HS1
      WRITE(6,27)
      WRITE(6,26)F,B1,B2,CF,C1,C2,TF,TS1,T1,T2,HS1
      READ(5,16)STEPF,STEPS1,STEPCF,STEPTF,STEPC2,OL
      L=2
```

```
      CALL DATA(L)
      WRITE(6,30)
      WRITE(6,29)UA1,UA2,HL2,HL3
      READ(5,18)KL1,KL2,KC2,TL1,TL2,TC2,TDC2,SDENS
      WRITE(6,31)
      WRITE(6,32)KL1,KL2,KC2,TL1,TL2,TC2,TDC2
      NC=0
      SDENS=1./SDENS
      IF(KMM.EQ.7)UA1=1.25*UA1
      IF(KMM.EQ.8)UA2=1.25*UA2
      IF(KMM.EQ.9)HL2=HL2*1.25
      IF(KMM.EQ.10)HL3=1.25*HL3
      CALL STEADY
      WRITE(6,28)
      WRITE(6,35)F,B1,B2,CF,C1,C2,TF,TS1,T1,SI
 707  CONTINUE
      N=9
      CALL INTEG(H,END,WRTE,N)
      WRITE(6,36)
      WRITE(6,35)F,B1,B2,CF,C1,C2,TF,TS1,T1,SI
 708  CONTINUE
 11   FORMAT(1X,I2)
 12   FORMAT(1X,12A5)
 13   FORMAT(1X,3A6)
 15   FORMAT(1X,3F6.3,3F8.5,4F6.1,F7.1)
 16   FORMAT(1X,2F6.3,F7.4,F5.1,F7.4,F4.1)
 17   FORMAT(1X,F5.2,F7.1,F4.1)
 18   FORMAT(1X,3F6.1,4F5.1,F7.2)
 21   FORMAT(1HK,37X,10HEXPERIMENT,I3)
 22   FORMAT(1HK,14X,12A5)
 23   FORMAT(1HK,31X,10HINPUT DATA)
 26   FORMAT(1X,14X,2HF=,F6.3,5H, B1=,F6.3,5H, B2=,F6.3,5H, CF=,F8.5,5H,
     1 C1=,F8.5/13X,5H  C2=,F8.5,5H, TF=,F6.1,6H, TS1=,F6.1,5H, T1=,F6.1
     1,5H, T2=,F6.1/13X,6H  HSI=,F7.1)
 25   FORMAT(1HJ,14X,18HINITIAL CONDITIONS)
 27   FORMAT(1HJ,14X,16HFINAL CONDITIONS )
 28   FORMAT(1HJ,14X,29HCALCULATED INITIAL CONDITIONS )
 29   FORMAT(15X,4HUA1=,F6.2,6H, UA2=,F6.2,6H, HL2=,F7.2,6H, HL3=,F7.2)
 30   FORMAT(1HJ,14X,21HCALCULATED PARAMETERS )
 31   FORMAT(1HJ,14X,19HCONTROLLER SETTINGS )
 32   FORMAT(15X,4HKL1=,F5.1,6H, KL2=,F6.1,6H, KC2=,F6.1,6H, TL1=,F5.1,6
     1H, TL2=,F5.1/13X,6H  TC2=,F5.1,7H, TDC2=,F4.1)
 33   FORMAT(1H1)
 34   FORMAT(15X,12A5)
 35   FORMAT(1X,14X,2HF=,F6.3,5H, B1=,F6.3,5H, B2=,F6.3,5H, CF=,F8.5,5H,
     1 C1=,F8.5/13X,5H  C2=,F8.5,5H, TF=,F6.1,6H, TS1=,F6.1,5H, T1=,F6.1
     2,5H, SI=,F6.3)
 36   FORMAT(1HJ,14X,27HCALCULATED FINAL CONDITIONS )
      END
```

```
      CALL DATA(L)
      WRITE(6,30)
      WRITE(6,29)UA1,UA2,HL2,HL3
      READ(5,18)KL1,KL2,KC2,TL1,TL2,TC2,TDC2,SDENS
      WRITE(6,31)
      WRITE(6,32)KL1,KL2,KC2,TL1,TL2,TC2,TDC2
      NC=0
      SDENS=1./SDENS
      IF(KMM.EQ.7)UA1=1.25*UA1
      IF(KMM.EQ.8)UA2=1.25*UA2
      IF(KMM.EQ.9)HL2=HL2*1.25
      IF(KMM.EQ.10)HL3=1.25*HL3
      CALL STEADY
      WRITE(6,28)
      WRITE(6,35)F,B1,B2,CF,C1,C2,TF,TS1,T1,S1
  707 CONTINUE
      N=9
      CALL INTEG(H,END,WRTE,N)
      WRITE(6,36)
      WRITE(6,35)F,B1,B2,CF,C1,C2,TF,TS1,T1,S1
  708 CONTINUE
   11 FORMAT(1X,I2)
   12 FORMAT(1X,12A5)
   13 FORMAT(1X,3A6)
   15 FORMAT(1X,3F6.3,3F8.5,4F6.1,F7.1)
   16 FORMAT(1X,2F6.3,F7.4,F5.1,F7.4,F4.1)
   17 FORMAT(1X,F5.2,F7.1,F4.1)
   18 FORMAT(1X,3F6.1,4F5.1,F7.2)
   21 FORMAT(1HK,37X,10HEXPERIMENT,I3)
   22 FORMAT(1HK,14X,12A5)
   23 FORMAT(1HK,31X,10HINPUT DATA)
   26 FORMAT(1X,14X,2HF=,F6.3,5H, B1=,F6.3,5H, B2=,F6.3,5H, CF=,F8.5,5H
     1 C1=,F8.5/13X,5H  C2=,F8.5,5H, TF=,F6.1,6H, TS1=,F6.1,5H, T1=,F6.
     1,5H, T2=,F6.1/13X,6H  HS1=,F7.1)
   25 FORMAT(1HJ,14X,18HINITIAL CONDITIONS)
   27 FORMAT(1HJ,14X,16HFINAL CONDITIONS )
   28 FORMAT(1HJ,14X,29HCALCULATED INITIAL CONDITIONS )
   29 FORMAT(15X,4HUA1=,F6.2,6H, UA2=,F6.2,6H, HL2=,F7.2,6H, HL3=,F7.2)
   30 FORMAT(1HJ,14X,21HCALCULATED PARAMETERS )
   31 FORMAT(1HJ,14X,19HCONTROLLER SETTINGS )
   32 FORMAT(15X,4HKL1=,F5.1,6H, KL2=,F6.1,6H, KC2=,F6.1,6H, TL1=,F5.1,
     1H, TL2=,F5.1/13X,6H  TC2=,F5.1,7H, TDC2=,F4.1)
   33 FORMAT(1H1)
   34 FORMAT(15X,12A5)
   35 FORMAT(1X,14X,2HF=,F6.3,5H, B1=,F6.3,5H, B2=,F6.3,5H, CF=,F8.5,5H
     1 C1=,F8.5/13X,5H  C2=,F8.5,5H, TF=,F6.1,6H, TS1=,F6.1,5H, T1=,F6.
     2,5H, S1=,F6.3)
   36 FORMAT(1HJ,14X,27HCALCULATED FINAL CONDITIONS )
      END
```

```
      SUBROUTINE INTEG(H,END,WRTE,N)
C
C     INTEGRATION SUBROUTINE
C
C     D(I)=DERIVATIVE OF EQUATUON I
C     Y(I)=VALUE OF THE ITH INTEGRAL
C
      DIMENSION A(4),B(4),G(4),Q(20),CE(20,4),COLL(20)
      REAL KL1,KL2,KC2
      COMMON F,B1,B2,SI,O1,O2,B10,B20,SIO,CF,C1,C2,C2R,V1,V2,W1
      COMMON W2,W1R,W2R,DENS1,DENS2,TS1,TF,T1,T2,UA1,UA2,HL2,HF
      COMMON H1,H2,HSI,STEPF,STEPCF,STEPTF,STEPSI,STEPC2,Y(15)
      COMMON D(15),E(20),C(20),SIGL1O,OL,KL1,KL2,KC2,TL1,TL2
      COMMON TC2,TDC2,TI(100),G1(100),G2(100),NC,HL1,HL3,SIGSIO
      COMMON SDENS,KMM,EW1,EW2
      LOGICAL TEST,CHCK
C
C  INITIALIZATION OF THE RUNGE-KUTTA-GILL INTEGRATION
C
      A(1)=.5
      A(2)=1.-SQRT(.5)
      A(3)=1.+SQRT(.5)
      A(4)=.16666667
      B(1)=2.
      B(2)=1.
      B(3)=1.
      B(4)=2.
      G(1)=.5
      G(2)=A(2)
      G(3)=A(3)
      G(4)=.5
C
      TEST=.FALSE.
      CHCK=.FALSE.
      TIME=WRTE-H/2.
      Y(1)=0.
      DO 201 I=1,N
 201  Q(I)=0.
      M=1
 202  CONTINUE
      DO 203 J=1,4
      CALL DYDT(J,H)
      DO 203 I=1,N
      X=A(J)*(D(I)-B(J)*Q(I))
      Y(I)=Y(I)+H*X
      Q(I)=Q(I)+3.*X-G(J)*D(I)
 203  CONTINUE
 204  NPERT=IFIX(Y(1))
      IF(TEST)GO TO 207
      IF(CHCK)GO TO 205
      IF(NPERT.NE.4)GO TO 205
      CALL STEP(TEST,CHCK)
```

```
      SUBROUTINE INTEG(H,END,WRTE,N)
C
C     INTEGRATION SUBROUTINE
C
C     D(I)=DERIVATIVE OF EQUATUON I
C     Y(I)=VALUE OF THE ITH INTEGRAL
C
      DIMENSION A(4),B(4),G(4),Q(20),CE(20,4),COLL(20)
      REAL KL1,KL2,KC2
      COMMON F,B1,B2,S1,D1,D2,B10,B20,S10,CF,C1,C2,C2R,V1,V2,W1
      COMMON W2,W1R,W2R,DENS1,DENS2,TS1,TF,T1,T2,UA1,UA2,HL2,HF
      COMMON H1,H2,HS1,STEPF,STEPCF,STEPTF,STEPS1,STEPC2,Y(15)
      COMMON D(15),E(20),C(20),SIGL10,DL,KL1,KL2,KC2,TL1,TL2
      COMMON TC2,TDC2,TI(100),G1(100),G2(100),NC,HL1,HL3,SIGS10
      COMMON SDENS,KMM,EW1,EW2
      LOGICAL TEST,CHCK
C
C    INITIALIZATION OF THE RUNGE-KUTTA-GILL INTEGRATION
C
      A(1)=.5
      A(2)=1.-SQRT(.5)
      A(3)=1.+SQRT(.5)
      A(4)=.1666667
      B(1)=2.
      B(2)=1.
      B(3)=1.
      B(4)=2.
      G(1)=.5
      G(2)=A(2)
      G(3)=A(3)
      G(4)=.5
C
      TEST=.FALSE.
      CHCK=.FALSE.
      TIME=WRTE-H/2.
      Y(1)=0.
      DO 201 I=1,N
  201 Q(I)=0.
      M=1
  202 CONTINUE
      DO 203 J=1,4
      CALL DYDT(J,H)
      DO 203 I=1,N
      X=A(J)*(D(I)-B(J)*Q(I))
      Y(I)=Y(I)+H*X
      Q(I)=Q(I)+3.*X-G(J)*D(I)
  203 CONTINUE
  204 NPERT=IFIX(Y(1))
      IF(TEST)GO TO 207
      IF(CHCK)GO TO 205
      IF(NPERT.NE.4)GO TO 205
      CALL STEP(TEST,CHCK)
```

```
      GO TO 205
 207  IF(NPERT.NE.7)GO TO 205
      CALL STEP(TEST,CHCK)
 205  IF(Y(1).LT.TIME)GO TO 202
      CALL PRINT(TIME,WRTE,COLL)
      IF(Y(1).LT.END-H/2.)GO TO 202
      RETURN
      END
```

```
      SUBROUTINE DYDT(J,H)
C
C     SUBROUTINE TO CALCULATE THE DERIVATIVES FOR THE INTEGRATION
C
      REAL KL1,KL2,KC2
      COMMON F,B1,B2,SI,O1,O2,B10,B20,SI0,CF,C1,C2,C2R,V1,V2,W1
      COMMON W2,W1R,W2R,DENS1,DENS2,TS1,TF,T1,T2,UA1,UA2,HL2,HF
      COMMON H1,H2,HSI,STEPF,STEPCF,STEPTF,STEPSI,STEPC2,Y(15)
      COMMON D(15),E(20),C(20),SIGL10,OL,KL1,KL2,KC2,TL1,TL2
      COMMON TC2,TDC2,TI(100),G1(100),G2(100),NC,HL1,HL3,SIGSI0
      COMMON SDENS,KMM,EW1,EW2
      NZ=20-IFIX(4.0/(B1*H))
      W1=Y(2)
      H1=Y(3)/W1
      C1=Y(4)/W1
      C(20)=C1
      E(20)=H1
      W2=Y(5)
      C2=Y(6)/W2
      EW1=2.05*(W1-W1R)
      EW2=2.05*(W2-W2R)
      SIGL1=10.*(EW1+Y(7))/KL1+SIGL10
      B1=1.33*(SIGL1**.481)
      DELV=3.9413*(EW2+Y(8))/KL2
      B2=B20*(10.**DELV)
      T1=(H1+32.1-6.*C1)/(1.-.454*C1)
      HF=TF*(1.-.454*CF)-32.1+6.0*CF
      H2=T2*(1.-.454*C2)+6.*C2-32.1
      Q2=UA2*(T1-T2)
      HO2=1066.1+.4*T2
      HVAP=1098.-.6*T1
      HO1=1066.1+.4*T1
      DHDC=6.18-.454*T2
      O2=(Q2-HL3+B1*(E(NZ)-H2-DHDC*(C(NZ)-C2)))/(DHDC*C2+HO2-H2)
      O1=(Q2+HL2)/HVAP
      IF(OL)301,301,302
 302  EC2=(C2R-C2)/.001
      FDERC2=(B1*(C2-C(NZ))-O2*C2)/(0.001*W2)
      SIGSI=100.*(EC2+Y(9)+TDC2*FDERC2)/KC2+SIGSI0
      SI=0.680*SDENS*(SIGSI**.455)
 301  TS1=(SI*(HSI+32.0)+T1*UA1)/(UA1+1.01*SI)
      Q1=UA1*(TS1-T1)
      D(1)=1.
      D(2)=F-B1-O1
      D(3)=F*HF+Q1-B1*H1-O1*HO1
      D(4)=F*CF-B1*C1
      D(5)=B1-B2-O2
      D(6)=B1*C(NZ)-B2*C2
      D(7)=EW1/TL1
      D(8)=EW2/TL2
      D(9)=EC2/TC2
      IF(J.LT.4)GO TO 304
```

```
      SUBROUTINE DYDT(J,H)
C
C     SUBROUTINE TO CALCULATE THE DERIVATIVES FOR THE INTEGRATION
C
      REAL KL1,KL2,KC2
      COMMON F,B1,B2,S1,O1,O2,B10,B20,S10,CF,C1,C2,C2R,V1,V2,W1
      COMMON W2,W1R,W2R,DENS1,DENS2,TS1,TF,T1,T2,UA1,UA2,HL2,HF
      COMMON H1,H2,HS1,STEPF,STEPCF,STEPTF,STEPS1,STEPC2,Y(15)
      COMMON D(15),E(20),C(20),SIGL10,OL,KL1,KL2,KC2,TL1,TL2
      COMMON TC2,TDC2,TI(100),G1(100),G2(100),NC,HL1,HL3,SIGS10
      COMMON SDENS,KMM,EW1,EW2
      N2=20-IFIX(4.0/(B1*H))
      W1=Y(2)
      H1=Y(3)/W1
      C1=Y(4)/W1
      C(20)=C1
      E(20)=H1
      W2=Y(5)
      C2=Y(6)/W2
      EW1=2.05*(W1-W1R)
      EW2=2.05*(W2-W2R)
      SIGL1=10.*(EW1+Y(7))/KL1+SIGL10
      B1=1.33*(SIGL1**.481)
      DELV=3.9413*(EW2+Y(8))/KL2
      B2=B20*(10.**DELV)
      T1=(H1+32.1-6.*C1)/(1.-.454*C1)
      HF=TF*(1.-.454*CF)-32.1+6.0*CF
      H2=T2*(1.-.454*C2)+6.*C2-32.1
      Q2=UA2*(T1-T2)
      HO2=1066.1+.4*T2
      HVAP=1098.-.6*T1
      HO1=1066.1+.4*T1
      DHDC=6.18-.454*T2
      O2=(Q2-HL3+B1*(E(N2)-H2-DHDC*(C(N2)-C2)))/(DHDC*C2+HO2-H2)
      O1=(Q2+HL2)/HVAP
      IF(OL)301,301,302
302   EC2=(C2R-C2)/.001
      FDERC2=(B1*(C2-C(N2))-O2*C2)/(0.001*W2)
      SIGS1=100.*(EC2+Y(9)+TDC2*FDERC2)/KC2+SIGS10
      S1=0.680*SDENS*(SIGS1**.455)
301   TS1=(S1*(HS1+32.0)+T1*UA1)/(UA1+1.01*S1)
      Q1=UA1*(TS1-T1)
      D(1)=1.
      D(2)=F-B1-O1
      D(3)=F*HF+Q1-B1*H1-O1*HO1
      D(4)=F*CF-B1*C1
      D(5)=B1-B2-O2
      D(6)=B1*C(N2)-B2*C2
      D(7)=EW1/TL1
      D(8)=EW2/TL2
      D(9)=EC2/TC2
      IF(J.LT.4)GO TO 304
```

```
      DO 303 JI=1,19
      C(JI)=C(JI+1)
  303 E(JI)=E(JI+1)
  304 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE STEP(TEST,CHCK)
C
C     THIS SUBROUTINE PERTURBATES THE SYSTEM OF EQUATIONS
C
      REAL KL1,KL2,KC2
      COMMON F,B1,B2,SI,O1,O2,B1O,B2O,SIO,CF,C1,C2,C2R,V1,V2,W1
      COMMON W2,W1R,W2R,DENS1,DENS2,TS1,TF,T1,T2,UA1,UA2,HL2,HF
      COMMON H1,H2,HSI,STEPF,STEPCF,STEPTF,STEPSI,STEPC2,Y(15)
      COMMON D(15),E(20),C(20),SIGL1O,OL,KL1,KL2,KC2,TL1,TL2
      COMMON TC2,TDC2,TI(100),G1(100),G2(100),NC,HL1,HL3,SIGSIO
      COMMON SDENS,KMM,EW1,EW2
      LOGICAL TEST,CHCK
      IF(TEST)GO TO 601
      F=F+STEPF
      SI=SI+STEPSI
      C2R=C2R+STEPC2
      CHCK=.TRUE.
      IF(ABS(STEPTF).GT.1.00)TEST=.TRUE.
      IF(ABS(STEPCF).GT..001)TEST=.TRUE.
      GO TO 610
 601  CF=CF+STEPCF
      TF=TF+STEPTF
      TEST=.FALSE.
 610  CONTINUE
      RETURN
      END
```

```
      SUBROUTINE STEP(TEST,CHCK)
C
C     THIS SUBROUTINE PERTURBATES THE SYSTEM OF EQUATIONS
C
      REAL KL1,KL2,KC2
      COMMON F,B1,B2,S1,O1,O2,B10,B20,S10,CF,C1,C2,C2R,V1,V2,W1
      COMMON W2,W1R,W2R,DENS1,DENS2,TS1,TF,T1,T2,UA1,UA2,HL2,HF
      COMMON H1,H2,HS1,STEPF,STEPCF,STEPTF,STEPS1,STEPC2,Y(15)
      COMMON D(15),E(20),C(20),SIGL10,OL,KL1,KL2,KC2,TL1,TL2
      COMMON TC2,TDC2,TI(100),G1(100),G2(100),NC,HL1,HL3,SIGS10
      COMMON SDENS,KMM,EW1,EW2
      LOGICAL TEST,CHCK
      IF(TEST)GO TO 601
      F=F+STEPF
      S1=S1+STEPS1
      C2R=C2R+STEPC2
      CHCK=.TRUE.
      IF(ABS(STEPTF).GT.1.00)TEST=.TRUE.
      IF(ABS(STEPCF).GT..001)TEST=.TRUE.
      GO TO 610
  601 CF=CF+STEPCF
      TF=TF+STEPTF
      TEST=.FALSE.
  610 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE PRINT(TIME,WRTE,COLL)
C
C     SUBROUTINE TO CONTROL PRINT-OUT
C
      REAL KL1,KL2,KC2
      COMMON F,B1,B2,SI,O1,O2,B10,B20,SIO,CF,C1,C2,C2R,V1,V2,W1
      COMMON W2,W1R,W2R,DENS1,DENS2,TS1,TF,T1,T2,UA1,UA2,HL2,HF
      COMMON H1,H2,HSI,STEPF,STEPCF,STEPTF,STEPSI,STEPC2,Y(15)
      COMMON D(15),E(20),C(20),SIGL1O,OL,KL1,KL2,KC2,TL1,TL2
      COMMON TC2,TDC2,TI(100),G1(100),G2(100),NC,HL1,HL3,SIGSIO
      COMMON SDENS,KMM,EW1,EW2
      DIMENSION COLL(15)
      NC=NC+1
      PC1=100.*C1
      PC2=100.*C2
      TT=Y(1)-4.0
      RL1=EW1*2.5+40.0
      RL2=EW2*2.5+55.0
      IF(NC.NE.1)GO TO 820
      WRITE(6,806)
      WRITE(6,801)
      WRITE(6,802)
 820  IF(NC.NE.52)GO TO 821
      WRITE(6,806)
      WRITE(6,804)
      WRITE(6,802)
 821  IF(NC.NE.104)GO TO 822
      WRITE(6,806)
      WRITE(6,804)
      WRITE(6,802)
 822  IF(NC.NE.156)GO TO 823
      WRITE(6,806)
      WRITE(6,804)
      WRITE(6,802)
 823  WRITE(6,803)TT,PC1,PC2,B1,B2,SI,O1,O2,RL1,RL2
      TI(NC)=Y(1)
      G1(NC)=C1
      G2(NC)=C2
      TIME=TIME+WRTE
      RETURN
 801  FORMAT(1HL)
 802  FORMAT(14X,58HTIME   C1     C2    B1    B2    SI    O1    O2    L1
     1    L2/)
 803  FORMAT(12X,F6.1,F6.3,F7.3,5F6.3,2F6.1)
 804  FORMAT(1HK,11X,7H..CONTD)
 805  FORMAT(1X,5E16.8)
 806  FORMAT(1H1)
      END
```

```
      SUBROUTINE PRINT(TIME,WRTE,COLL)
C
C     SUBROUTINE TO CONTROL PRINT-OUT
C
      REAL KL1,KL2,KC2
      COMMON F,B1,B2,S1,O1,O2,B10,B20,S10,CF,C1,C2,C2R,V1,V2,W1
      COMMON W2,W1R,W2R,DENS1,DENS2,TS1,TF,T1,T2,UA1,UA2,HL2,HF
      COMMON H1,H2,HS1,STEPF,STEPCF,STEPTF,STEPS1,STEPC2,Y(15)
      COMMON D(15),E(20),C(20),SIGL10,OL,KL1,KL2,KC2,TL1,TL2
      COMMON TC2,TDC2,TI(100),G1(100),G2(100),NC,HL1,HL3,SIGS10
      COMMON SDENS,KMM,EW1,EW2
      DIMENSION COLL(15)
      NC=NC+1
      PC1=100.*C1
      PC2=100.*C2
      TT=Y(1)-4.0
      RL1=EW1*2.5+40.0
      RL2=EW2*2.5+55.0
      IF(NC.NE.1)GO TO 820
      WRITE(6,806)
      WRITE(6,801)
      WRITE(6,802)
  820 IF(NC.NE.52)GO TO 821
      WRITE(6,806)
      WRITE(6,804)
      WRITE(6,802)
  821 IF(NC.NE.104)GO TO 822
      WRITE(6,806)
      WRITE(6,804)
      WRITE(6,802)
  822 IF(NC.NE.156)GO TO 823
      WRITE(6,806)
      WRITE(6,804)
      WRITE(6,802)
  823 WRITE(6,803)TT,PC1,PC2,B1,B2,S1,O1,O2,RL1,RL2
      TI(NC)=Y(1)
      G1(NC)=C1
      G2(NC)=C2
      TIME=TIME+WRTE
      RETURN
  801 FORMAT(1H1)
  802 FORMAT(14X,58HTIME     C1      C2      B1      B2      S1      O1      O2      L
     1    L2/)
  803 FORMAT(12X,F6.1,F6.3,F7.3,5F6.3,2F6.1)
  804 FORMAT(1HK,11X,7H..CONTD)
  805 FORMAT(1X,5E16.8)
  806 FORMAT(1H1)
      END
```

APPENDIX 8

SIMULATED RESULTS

Included in this appendix are the computer results for the experiments of this work. These tables include the transient data as well as the experimental and calculated steady state data before and after each experiment.

The parameters designated L_1 and L_2 are the change in holdup of the first and second effects respectively, translated into liquid level transmitter output. As can be seen the change in these levels was not very large and since the liquid level records were very noisy a meaningful comparison of predicted and experimental transient behavior could not be made. Moreover, except for the possibility of exceeding physical limits these parameters are of secondary dynamic interest.

EXPERIMENT 1

OPEN LOOP RESPONSE TO A STEP UP IN FEED RATE

INPUT DATA

INITIAL CONDITIONS
F= 2.950, B1= 1.920, B2= 0.910, CF= 0.03120, C1= 0.04790
C2= 0.10120, TF= 99.0, TS1= 214.0, T1= 195.0, T2= 150.0
HSI= 1175.3

FINAL CONDITIONS
F= 3.490, B1= 2.530, B2= 1.550, CF= 0.03040, C1= 0.04200
C2= 0.06840, TF= 95.5, TS1= 210.8, T1= 192.2, T2= 150.0
HSI= 1175.3

CALCULATED PARAMETERS
UA1= 68.30, UA2= 22.10, HL2= 14.04, HL3= 56.18

CONTROLLER SETTINGS
KL1= 80.0, KL2= 80.0, KC2= 130.0, TL1= 6.0, TL2= 6.0
TC2= 7.0, TDC2= 5.0

CALCULATED INITIAL CONDITIONS
F= 2.950, B1= 1.923, B2= 0.910, CF= 0.03120, C1= 0.04786
C2= 0.10118, TF= 99.0, TS1= 213.8, T1= 194.9, SI= 1.298

EXPERIMENT 1

OPEN LOOP RESPONSE TO A STEP UP IN FEED RATE

INPUT DATA

INITIAL CONDITIONS
F= 2.950, B1= 1.920, B2= 0.910, CF= 0.03120, C1= 0.04790
C2= 0.10120, TF= 99.0, TS1= 214.0, T1= 195.0, T2= 150.0
HS1= 1175.3

FINAL CONDITIONS
F= 3.490, B1= 2.530, B2= 1.550, CF= 0.03040, C1= 0.04200
C2= 0.06840, TF= 95.5, TS1= 210.8, T1= 192.2, T2= 150.0
HS1= 1175.3

CALCULATED PARAMETERS
UA1= 68.30, UA2= 22.10, HL2= 14.04, HL3= 56.18

CONTROLLER SETTINGS
KL1= 80.0, KL2= 80.0, KC2= 130.0, TL1= 6.0, TL2= 6.0
TC2= 7.0, TDC2= 5.0

CALCULATED INITIAL CONDITIONS
F= 2.950, B1= 1.923, B2= 0.910, CF= 0.03120, C1= 0.04786
C2= 0.10118, TF= 99.0, TS1= 213.8, T1= 194.9, S1= 1.298

TIME	C1	C2	B1	B2	SI	O1	O2	L1	L2
-2.0	4.786	10.118	1.923	0.910	1.298	1.027	1.013	40.0	55.0
-0.0	4.786	10.118	1.923	0.910	1.298	1.027	1.013	40.0	55.0
2.0	4.741	10.088	2.035	0.936	1.298	0.995	0.988	44.7	55.6
4.0	4.689	9.999	2.161	1.020	1.298	0.979	0.975	48.8	57.0
6.0	4.632	9.857	2.280	1.152	1.298	0.969	0.970	51.8	58.8
8.0	4.582	9.679	2.389	1.312	1.298	0.967	0.971	53.8	60.1
10.0	4.537	9.478	2.483	1.474	1.298	0.967	0.975	54.7	60.8
12.0	4.498	9.264	2.562	1.613	1.298	0.966	0.978	54.7	60.9
14.0	4.463	9.044	2.625	1.715	1.298	0.966	0.980	53.9	60.3
16.0	4.433	8.825	2.673	1.779	1.298	0.966	0.982	52.6	59.5
18.0	4.406	8.614	2.706	1.813	1.298	0.966	0.984	50.9	58.6
20.0	4.381	8.414	2.726	1.825	1.298	0.966	0.984	49.0	57.7
22.0	4.360	8.229	2.734	1.822	1.298	0.966	0.985	46.8	56.9
24.0	4.341	8.060	2.731	1.807	1.298	0.966	0.985	44.7	56.2
26.0	4.324	7.909	2.718	1.785	1.298	0.966	0.984	42.6	55.6
28.0	4.309	7.776	2.699	1.757	1.298	0.966	0.983	40.8	55.1
30.0	4.296	7.661	2.673	1.725	1.298	0.966	0.982	39.1	54.8
32.0	4.284	7.562	2.644	1.690	1.298	0.966	0.981	37.7	54.4
34.0	4.274	7.478	2.613	1.654	1.298	0.966	0.980	36.6	54.2
36.0	4.265	7.408	2.582	1.618	1.298	0.966	0.978	35.9	54.0
38.0	4.257	7.351	2.552	1.584	1.298	0.966	0.977	35.5	53.9
40.0	4.250	7.304	2.525	1.552	1.298	0.966	0.976	35.3	53.8
42.0	4.244	7.265	2.502	1.525	1.298	0.966	0.975	35.4	53.8
44.0	4.239	7.234	2.483	1.502	1.298	0.966	0.974	35.7	53.9
46.0	4.235	7.209	2.470	1.484	1.298	0.966	0.974	36.2	54.0
48.0	4.231	7.187	2.461	1.472	1.298	0.966	0.974	36.9	54.1
50.0	4.227	7.168	2.456	1.465	1.298	0.966	0.973	37.5	54.3
52.0	4.224	7.151	2.456	1.464	1.298	0.966	0.973	38.2	54.5
54.0	4.222	7.135	2.460	1.467	1.298	0.966	0.973	38.9	54.7
56.0	4.220	7.119	2.466	1.475	1.298	0.966	0.974	39.5	54.9
58.0	4.218	7.103	2.474	1.485	1.298	0.966	0.974	40.1	55.0
60.0	4.216	7.087	2.484	1.497	1.298	0.966	0.974	40.6	55.2
62.0	4.214	7.070	2.494	1.509	1.298	0.966	0.975	40.9	55.3
64.0	4.213	7.054	2.504	1.522	1.298	0.966	0.975	41.2	55.4
66.0	4.212	7.037	2.513	1.534	1.298	0.966	0.976	41.4	55.4
68.0	4.211	7.020	2.522	1.545	1.298	0.966	0.976	41.4	55.4
70.0	4.210	7.003	2.529	1.555	1.298	0.966	0.976	41.4	55.4
72.0	4.209	6.987	2.535	1.562	1.298	0.966	0.977	41.3	55.4
74.0	4.209	6.971	2.540	1.568	1.298	0.966	0.977	41.2	55.3
76.0	4.208	6.957	2.543	1.572	1.298	0.966	0.977	41.0	55.3
78.0	4.208	6.943	2.545	1.573	1.298	0.966	0.977	40.8	55.2
80.0	4.207	6.931	2.545	1.574	1.298	0.966	0.977	40.6	55.2
82.0	4.207	6.920	2.544	1.573	1.298	0.966	0.977	40.4	55.1
84.0	4.207	6.910	2.543	1.571	1.298	0.966	0.977	40.2	55.1
86.0	4.206	6.901	2.540	1.568	1.298	0.966	0.977	40.0	55.0
88.0	4.206	6.894	2.538	1.565	1.298	0.966	0.977	39.9	55.0
90.0	4.206	6.888	2.535	1.561	1.298	0.966	0.977	39.7	54.9
92.0	4.206	6.884	2.532	1.557	1.298	0.966	0.976	39.7	54.9
94.0	4.205	6.880	2.529	1.554	1.298	0.966	0.976	39.6	54.9
96.0	4.205	6.877	2.526	1.550	1.298	0.966	0.976	39.6	54.9
98.0	4.205	6.875	2.524	1.547	1.298	0.966	0.976	39.6	54.9

TIME	C1	C2	B1	B2	S1	O1	O2	L1	L2
-2.0	4.786	10.118	1.923	0.910	1.298	1.027	1.013	40.0	55.0
-0.0	4.786	10.118	1.923	0.910	1.298	1.027	1.013	40.0	55.0
2.0	4.741	10.088	2.035	0.936	1.298	0.995	0.988	44.7	55.6
4.0	4.689	9.999	2.161	1.020	1.298	0.979	0.975	48.8	57.0
6.0	4.632	9.857	2.280	1.152	1.298	0.969	0.970	51.8	58.8
8.0	4.582	9.679	2.389	1.312	1.298	0.967	0.971	53.8	60.1
10.0	4.537	9.478	2.483	1.474	1.298	0.967	0.975	54.7	60.8
12.0	4.498	9.264	2.562	1.613	1.298	0.966	0.978	54.7	60.9
14.0	4.463	9.044	2.625	1.715	1.298	0.966	0.980	53.9	60.3
16.0	4.433	8.825	2.673	1.779	1.298	0.966	0.982	52.6	59.5
18.0	4.406	8.614	2.706	1.813	1.298	0.966	0.984	50.9	58.6
20.0	4.381	8.414	2.726	1.825	1.298	0.966	0.984	49.0	57.7
22.0	4.360	8.229	2.734	1.822	1.298	0.966	0.985	46.8	56.9
24.0	4.341	8.060	2.731	1.807	1.298	0.966	0.985	44.7	56.2
26.0	4.324	7.909	2.718	1.785	1.298	0.966	0.984	42.6	55.6
28.0	4.309	7.776	2.699	1.757	1.298	0.966	0.983	40.8	55.1
30.0	4.296	7.661	2.673	1.725	1.298	0.966	0.982	39.1	54.8
32.0	4.284	7.562	2.644	1.690	1.298	0.966	0.981	37.7	54.4
34.0	4.274	7.478	2.613	1.654	1.298	0.966	0.980	36.6	54.2
36.0	4.265	7.408	2.582	1.618	1.298	0.966	0.978	35.9	54.0
38.0	4.257	7.351	2.552	1.584	1.298	0.966	0.977	35.5	53.9
40.0	4.250	7.304	2.525	1.552	1.298	0.966	0.976	35.3	53.8
42.0	4.244	7.265	2.502	1.525	1.298	0.966	0.975	35.4	53.8
44.0	4.239	7.234	2.483	1.502	1.298	0.966	0.974	35.7	53.9
46.0	4.235	7.209	2.470	1.484	1.298	0.966	0.974	36.2	54.0
48.0	4.231	7.187	2.461	1.472	1.298	0.966	0.974	36.9	54.1
50.0	4.227	7.168	2.456	1.465	1.298	0.966	0.973	37.5	54.3
52.0	4.224	7.151	2.456	1.464	1.298	0.966	0.973	38.2	54.5
54.0	4.222	7.135	2.460	1.467	1.298	0.966	0.973	38.9	54.7
56.0	4.220	7.119	2.466	1.475	1.298	0.966	0.974	39.5	54.9
58.0	4.218	7.103	2.474	1.485	1.298	0.966	0.974	40.1	55.0
60.0	4.216	7.087	2.484	1.497	1.298	0.966	0.974	40.6	55.2
62.0	4.214	7.070	2.494	1.509	1.298	0.966	0.975	40.9	55.3
64.0	4.213	7.054	2.504	1.522	1.298	0.966	0.975	41.2	55.4
66.0	4.212	7.037	2.513	1.534	1.298	0.966	0.976	41.4	55.4
68.0	4.211	7.020	2.522	1.545	1.298	0.966	0.976	41.4	55.4
70.0	4.210	7.003	2.529	1.555	1.298	0.966	0.976	41.4	55.4
72.0	4.209	6.987	2.535	1.562	1.298	0.966	0.977	41.3	55.4
74.0	4.209	6.971	2.540	1.568	1.298	0.966	0.977	41.2	55.3
76.0	4.208	6.957	2.543	1.572	1.298	0.966	0.977	41.0	55.3
78.0	4.208	6.943	2.545	1.573	1.298	0.966	0.977	40.8	55.2
80.0	4.207	6.931	2.545	1.574	1.298	0.966	0.977	40.6	55.2
82.0	4.207	6.920	2.544	1.573	1.298	0.966	0.977	40.4	55.1
84.0	4.207	6.910	2.543	1.571	1.298	0.966	0.977	40.2	55.1
86.0	4.206	6.901	2.540	1.568	1.298	0.966	0.977	40.0	55.0
88.0	4.206	6.894	2.538	1.565	1.298	0.966	0.977	39.9	55.0
90.0	4.206	6.888	2.535	1.561	1.298	0.966	0.977	39.7	54.9
92.0	4.206	6.884	2.532	1.557	1.298	0.966	0.976	39.7	54.9
94.0	4.205	6.880	2.529	1.554	1.298	0.966	0.976	39.6	54.9
96.0	4.205	6.877	2.526	1.550	1.298	0.966	0.976	39.6	54.9
98.0	4.205	6.875	2.524	1.547	1.298	0.966	0.976	39.6	54.9

..CONTD

TIME	C1	C2	B1	B2	SI	O1	O2	L1	L2
100.0	4.205	6.873	2.522	1.545	1.298	0.966	0.976	39.6	54.9
102.0	4.205	6.872	2.520	1.543	1.298	0.966	0.976	39.6	54.9
104.0	4.205	6.871	2.519	1.541	1.298	0.966	0.976	39.7	54.9
106.0	4.205	6.870	2.518	1.541	1.298	0.966	0.976	39.7	54.9
108.0	4.205	6.870	2.518	1.540	1.298	0.966	0.976	39.8	54.9
110.0	4.205	6.869	2.518	1.540	1.298	0.966	0.976	39.9	55.0
112.0	4.205	6.869	2.518	1.541	1.298	0.966	0.976	39.9	55.0
114.0	4.204	6.868	2.519	1.542	1.298	0.966	0.976	40.0	55.0
116.0	4.204	6.868	2.520	1.543	1.298	0.966	0.976	40.0	55.0
118.0	4.204	6.867	2.521	1.544	1.298	0.966	0.976	40.1	55.0
120.0	4.204	6.866	2.522	1.545	1.298	0.966	0.976	40.1	55.0
122.0	4.204	6.865	2.523	1.546	1.298	0.966	0.976	40.1	55.0
124.0	4.204	6.865	2.524	1.547	1.298	0.966	0.976	40.1	55.0
126.0	4.204	6.864	2.524	1.548	1.298	0.966	0.976	40.1	55.0
128.0	4.204	6.863	2.525	1.549	1.298	0.966	0.976	40.1	55.0
130.0	4.204	6.862	2.525	1.550	1.298	0.966	0.976	40.1	55.0
132.0	4.204	6.861	2.526	1.550	1.298	0.966	0.976	40.1	55.0
134.0	4.204	6.860	2.526	1.550	1.298	0.966	0.976	40.1	55.0
136.0	4.204	6.859	2.526	1.551	1.298	0.966	0.976	40.1	55.0
138.0	4.204	6.858	2.526	1.551	1.298	0.966	0.976	40.1	55.0
140.0	4.204	6.858	2.526	1.550	1.298	0.966	0.976	40.0	55.0
142.0	4.204	6.857	2.526	1.550	1.298	0.966	0.976	40.0	55.0
144.0	4.204	6.857	2.526	1.550	1.298	0.966	0.976	40.0	55.0
146.0	4.204	6.856	2.525	1.550	1.298	0.966	0.976	40.0	55.0
148.0	4.204	6.856	2.525	1.549	1.298	0.966	0.976	40.0	55.0
150.0	4.204	6.856	2.525	1.549	1.298	0.966	0.976	40.0	55.0
152.0	4.204	6.855	2.525	1.549	1.298	0.966	0.976	40.0	55.0
154.0	4.204	6.855	2.524	1.548	1.298	0.966	0.976	40.0	55.0
156.0	4.204	6.855	2.524	1.548	1.298	0.966	0.976	40.0	55.0
158.0	4.204	6.855	2.524	1.548	1.298	0.966	0.976	40.0	55.0
160.0	4.204	6.855	2.524	1.548	1.298	0.966	0.976	40.0	55.0
162.0	4.204	6.855	2.524	1.547	1.298	0.966	0.976	40.0	55.0
164.0	4.204	6.855	2.524	1.547	1.298	0.966	0.976	40.0	55.0
166.0	4.204	6.855	2.524	1.547	1.298	0.966	0.976	40.0	55.0
168.0	4.204	6.856	2.524	1.547	1.298	0.966	0.976	40.0	55.0
170.0	4.204	6.856	2.524	1.547	1.298	0.966	0.976	40.0	55.0
172.0	4.204	6.856	2.524	1.548	1.298	0.966	0.976	40.0	55.0
174.0	4.204	6.856	2.524	1.548	1.298	0.966	0.976	40.0	55.0
176.0	4.204	6.856	2.524	1.548	1.298	0.966	0.976	40.0	55.0
178.0	4.204	6.856	2.524	1.548	1.298	0.966	0.976	40.0	55.0
180.0	4.204	6.856	2.524	1.548	1.298	0.966	0.976	40.0	55.0

CALCULATED FINAL CONDITIONS
F= 3.491, B1= 2.524, B2= 1.548, CF= 0.03040, C1= 0.04204
C2= 0.06856, TF= 93.5, TS1= 211.2, T1= 192.3, SI= 1.298

..CONTD

TIME	C1	C2	B1	B2	S1	O1	O2	L1	L2
100.0	4.205	6.873	2.522	1.545	1.298	0.966	0.976	39.6	54.9
102.0	4.205	6.872	2.520	1.543	1.298	0.966	0.976	39.6	54.9
104.0	4.205	6.871	2.519	1.541	1.298	0.966	0.976	39.7	54.9
106.0	4.205	6.870	2.518	1.541	1.298	0.966	0.976	39.7	54.9
108.0	4.205	6.870	2.518	1.540	1.298	0.966	0.976	39.8	54.9
110.0	4.205	6.869	2.518	1.540	1.298	0.966	0.976	39.9	55.0
112.0	4.205	6.869	2.518	1.541	1.298	0.966	0.976	39.9	55.0
114.0	4.204	6.868	2.519	1.542	1.298	0.966	0.976	40.0	55.0
116.0	4.204	6.868	2.520	1.543	1.298	0.966	0.976	40.0	55.0
118.0	4.204	6.867	2.521	1.544	1.298	0.966	0.976	40.1	55.0
120.0	4.204	6.866	2.522	1.545	1.298	0.966	0.976	40.1	55.0
122.0	4.204	6.865	2.523	1.546	1.298	0.966	0.976	40.1	55.0
124.0	4.204	6.865	2.524	1.547	1.298	0.966	0.976	40.1	55.0
126.0	4.204	6.864	2.524	1.548	1.298	0.966	0.976	40.1	55.0
128.0	4.204	6.863	2.525	1.549	1.298	0.966	0.976	40.1	55.0
130.0	4.204	6.862	2.525	1.550	1.298	0.966	0.976	40.1	55.0
132.0	4.204	6.861	2.526	1.550	1.298	0.966	0.976	40.1	55.0
134.0	4.204	6.860	2.526	1.550	1.298	0.966	0.976	40.1	55.0
136.0	4.204	6.859	2.526	1.551	1.298	0.966	0.976	40.1	55.0
138.0	4.204	6.858	2.526	1.551	1.298	0.966	0.976	40.1	55.0
140.0	4.204	6.858	2.526	1.550	1.298	0.966	0.976	40.0	55.0
142.0	4.204	6.857	2.526	1.550	1.298	0.966	0.976	40.0	55.0
144.0	4.204	6.857	2.526	1.550	1.298	0.966	0.976	40.0	55.0
146.0	4.204	6.856	2.525	1.550	1.298	0.966	0.976	40.0	55.0
148.0	4.204	6.856	2.525	1.549	1.298	0.966	0.976	40.0	55.0
150.0	4.204	6.856	2.525	1.549	1.298	0.966	0.976	40.0	55.0
152.0	4.204	6.855	2.525	1.549	1.298	0.966	0.976	40.0	55.0
154.0	4.204	6.855	2.524	1.548	1.298	0.966	0.976	40.0	55.0
156.0	4.204	6.855	2.524	1.548	1.298	0.966	0.976	40.0	55.0
158.0	4.204	6.855	2.524	1.548	1.298	0.966	0.976	40.0	55.0
160.0	4.204	6.855	2.524	1.548	1.298	0.966	0.976	40.0	55.0
162.0	4.204	6.855	2.524	1.547	1.298	0.966	0.976	40.0	55.0
164.0	4.204	6.855	2.524	1.547	1.298	0.966	0.976	40.0	55.0
166.0	4.204	6.855	2.524	1.547	1.298	0.966	0.976	40.0	55.0
168.0	4.204	6.856	2.524	1.547	1.298	0.966	0.976	40.0	55.0
170.0	4.204	6.856	2.524	1.547	1.298	0.966	0.976	40.0	55.0
172.0	4.204	6.856	2.524	1.548	1.298	0.966	0.976	40.0	55.0
174.0	4.204	6.856	2.524	1.548	1.298	0.966	0.976	40.0	55.0
176.0	4.204	6.856	2.524	1.548	1.298	0.966	0.976	40.0	55.0
178.0	4.204	6.856	2.524	1.548	1.298	0.966	0.976	40.0	55.0
180.0	4.204	6.856	2.524	1.548	1.298	0.966	0.976	40.0	55.0

CALCULATED FINAL CONDITIONS

F= 3.491, B1= 2.524, B2= 1.548, CF= 0.03040, C1= 0.04204

C2= 0.06856, TF= 93.5, TS1= 211.2, T1= 192.3, S1= 1.298

EXPERIMENT 2

OPEN LOOP RESPONSE TO A STEP DOWN IN FEED RATE

INPUT DATA

INITIAL CONDITIONS
F= 3.800, B1= 2.800, B2= 1.840, CF= 0.03100, C1= 0.04210
C2= 0.06480, TF= 93.0, TS1= 214.0, T1= 190.5, T2= 150.0
HSI= 1175.5

FINAL CONDITIONS
F= 3.400, B1= 2.400, B2= 1.430, CF= 0.03220, C1= 0.04550
C2= 0.07750, TF= 83.0, TS1= 214.0, T1= 191.0, T2= 150.0
HSI= 1175.5

CALCULATED PARAMETERS
UA1= 58.04, UA2= 23.68, HL2= 19.57, HL3= 78.28

CONTROLLER SETTINGS
KL1= 80.0, KL2= 160.0, KC2= 130.0, TL1= 8.5, TL2= 6.0
TC2= 7.0, TDC2= 5.0

CALCULATED INITIAL CONDITIONS
F= 3.811, B1= 2.816, B2= 1.830, CF= 0.03104, C1= 0.04202
C2= 0.06465, TF= 93.0, TS1= 213.7, T1= 190.5, SI= 1.358

TIME	C1	C2	B1	B2	SI	O1	O2	L1	L2
-2.0	4.202	6.465	2.816	1.830	1.358	0.996	0.986	40.0	55.0
-0.0	4.202	6.465	2.816	1.830	1.358	0.996	0.986	40.0	55.0
2.0	4.225	6.475	2.758	1.815	1.358	1.021	1.009	36.4	54.7
4.0	4.260	6.503	2.688	1.771	1.358	1.017	1.004	32.9	53.8
6.0	4.300	6.540	2.618	1.714	1.358	1.008	0.992	30.3	52.9
8.0	4.335	6.588	2.549	1.648	1.358	1.007	0.987	28.4	52.0
10.0	4.366	6.647	2.484	1.576	1.358	1.006	0.984	27.2	51.2
12.0	4.393	6.713	2.424	1.503	1.358	1.006	0.981	26.7	50.5
14.0	4.416	6.787	2.372	1.433	1.358	1.006	0.979	26.7	50.0
16.0	4.436	6.865	2.328	1.369	1.358	1.006	0.977	27.3	49.7
18.0	4.454	6.945	2.294	1.312	1.358	1.006	0.976	28.2	49.6
20.0	4.469	7.025	2.269	1.266	1.358	1.006	0.975	29.5	49.8
22.0	4.482	7.104	2.253	1.230	1.358	1.006	0.974	30.9	50.2
24.0	4.494	7.179	2.246	1.204	1.358	1.006	0.974	32.5	50.8
26.0	4.504	7.249	2.246	1.191	1.358	1.006	0.974	34.1	51.6
28.0	4.512	7.313	2.252	1.188	1.358	1.006	0.974	35.6	52.4
30.0	4.520	7.371	2.264	1.195	1.358	1.006	0.975	37.1	53.4
32.0	4.527	7.422	2.278	1.211	1.358	1.006	0.975	38.4	54.4
34.0	4.532	7.466	2.295	1.234	1.358	1.006	0.976	39.6	55.3
36.0	4.537	7.503	2.313	1.264	1.358	1.006	0.977	40.6	56.1
38.0	4.542	7.534	2.332	1.297	1.358	1.006	0.977	41.4	56.8
40.0	4.546	7.559	2.350	1.332	1.358	1.006	0.978	42.0	57.3
42.0	4.549	7.579	2.366	1.366	1.358	1.006	0.979	42.5	57.6
44.0	4.552	7.595	2.382	1.398	1.358	1.006	0.979	42.8	57.7
46.0	4.554	7.607	2.395	1.426	1.358	1.006	0.980	42.9	57.7
48.0	4.557	7.615	2.407	1.448	1.358	1.006	0.980	42.9	57.5
50.0	4.559	7.622	2.416	1.466	1.358	1.006	0.981	42.8	57.2
52.0	4.561	7.626	2.424	1.477	1.358	1.006	0.981	42.6	56.9
54.0	4.562	7.629	2.429	1.484	1.358	1.006	0.981	42.3	56.5
56.0	4.564	7.631	2.433	1.487	1.358	1.006	0.981	42.0	56.2
58.0	4.565	7.633	2.434	1.486	1.358	1.006	0.981	41.7	55.8
60.0	4.566	7.634	2.435	1.482	1.358	1.006	0.981	41.4	55.5
62.0	4.567	7.636	2.434	1.477	1.358	1.006	0.981	41.0	55.2
64.0	4.568	7.638	2.432	1.470	1.358	1.006	0.981	40.7	55.0
66.0	4.568	7.640	2.429	1.463	1.358	1.006	0.981	40.4	54.8
68.0	4.569	7.643	2.425	1.455	1.358	1.006	0.981	40.1	54.7
70.0	4.570	7.646	2.422	1.448	1.358	1.006	0.981	39.9	54.6
72.0	4.570	7.650	2.418	1.441	1.358	1.006	0.981	39.7	54.5
74.0	4.571	7.655	2.414	1.435	1.358	1.006	0.981	39.6	54.5
76.0	4.571	7.659	2.410	1.429	1.358	1.006	0.980	39.5	54.5
78.0	4.571	7.665	2.407	1.424	1.358	1.006	0.980	39.4	54.5
80.0	4.572	7.670	2.403	1.420	1.358	1.006	0.980	39.4	54.5
82.0	4.572	7.675	2.401	1.416	1.358	1.006	0.980	39.3	54.6
84.0	4.572	7.681	2.398	1.413	1.358	1.006	0.980	39.4	54.6
86.0	4.572	7.686	2.397	1.411	1.358	1.006	0.980	39.4	54.7
88.0	4.573	7.691	2.395	1.410	1.358	1.006	0.980	39.5	54.7
90.0	4.573	7.696	2.394	1.409	1.358	1.006	0.980	39.5	54.8
92.0	4.573	7.700	2.394	1.409	1.358	1.006	0.980	39.6	54.8
94.0	4.573	7.704	2.394	1.409	1.358	1.006	0.980	39.7	54.9
96.0	4.573	7.708	2.394	1.410	1.358	1.006	0.980	39.8	54.9
98.0	4.573	7.712	2.394	1.411	1.358	1.006	0.980	39.8	55.0

TIME	C1	C2	B1	B2	S1	O1	O2	L1	L2
-2.0	4.202	6.465	2.816	1.830	1.358	0.996	0.986	40.0	55.0
-0.0	4.202	6.465	2.816	1.830	1.358	0.996	0.986	40.0	55.0
2.0	4.225	6.475	2.758	1.815	1.358	1.021	1.009	36.4	54.7
4.0	4.260	6.503	2.688	1.771	1.358	1.017	1.004	32.9	53.8
6.0	4.300	6.540	2.618	1.714	1.358	1.008	0.992	30.3	52.9
8.0	4.335	6.588	2.549	1.648	1.358	1.007	0.987	28.4	52.0
10.0	4.366	6.647	2.484	1.576	1.358	1.006	0.984	27.2	51.2
12.0	4.393	6.713	2.424	1.503	1.358	1.006	0.981	26.7	50.5
14.0	4.416	6.787	2.372	1.433	1.358	1.006	0.979	26.7	50.0
16.0	4.436	6.865	2.328	1.369	1.358	1.006	0.977	27.3	49.7
18.0	4.454	6.945	2.294	1.312	1.358	1.006	0.976	28.2	49.6
20.0	4.469	7.025	2.269	1.266	1.358	1.006	0.975	29.5	49.8
22.0	4.482	7.104	2.253	1.230	1.358	1.006	0.974	30.9	50.2
24.0	4.494	7.179	2.246	1.204	1.358	1.006	0.974	32.5	50.8
26.0	4.504	7.249	2.246	1.191	1.358	1.006	0.974	34.1	51.6
28.0	4.512	7.313	2.252	1.188	1.358	1.006	0.974	35.6	52.4
30.0	4.520	7.371	2.264	1.195	1.358	1.006	0.975	37.1	53.4
32.0	4.527	7.422	2.278	1.211	1.358	1.006	0.975	38.4	54.4
34.0	4.532	7.466	2.295	1.234	1.358	1.006	0.976	39.6	55.3
36.0	4.537	7.503	2.313	1.264	1.358	1.006	0.977	40.6	56.1
38.0	4.542	7.534	2.332	1.297	1.358	1.006	0.977	41.4	56.8
40.0	4.546	7.559	2.350	1.332	1.358	1.006	0.978	42.0	57.3
42.0	4.549	7.579	2.366	1.366	1.358	1.006	0.979	42.5	57.6
44.0	4.552	7.595	2.382	1.398	1.358	1.006	0.979	42.8	57.7
46.0	4.554	7.607	2.395	1.426	1.358	1.006	0.980	42.9	57.7
48.0	4.557	7.615	2.407	1.448	1.358	1.006	0.980	42.9	57.5
50.0	4.559	7.622	2.416	1.466	1.358	1.006	0.981	42.8	57.2
52.0	4.561	7.626	2.424	1.477	1.358	1.006	0.981	42.6	56.9
54.0	4.562	7.629	2.429	1.484	1.358	1.006	0.981	42.3	56.5
56.0	4.564	7.631	2.433	1.487	1.358	1.006	0.981	42.0	56.2
58.0	4.565	7.633	2.434	1.486	1.358	1.006	0.981	41.7	55.8
60.0	4.566	7.634	2.435	1.482	1.358	1.006	0.981	41.4	55.5
62.0	4.567	7.636	2.434	1.477	1.358	1.006	0.981	41.0	55.2
64.0	4.568	7.638	2.432	1.470	1.358	1.006	0.981	40.7	55.0
66.0	4.568	7.640	2.429	1.463	1.358	1.006	0.981	40.4	54.8
68.0	4.569	7.643	2.425	1.455	1.358	1.006	0.981	40.1	54.7
70.0	4.570	7.646	2.422	1.448	1.358	1.006	0.981	39.9	54.6
72.0	4.570	7.650	2.418	1.441	1.358	1.006	0.981	39.7	54.5
74.0	4.571	7.655	2.414	1.435	1.358	1.006	0.981	39.6	54.5
76.0	4.571	7.659	2.410	1.429	1.358	1.006	0.980	39.5	54.5
78.0	4.571	7.665	2.407	1.424	1.358	1.006	0.980	39.4	54.5
80.0	4.572	7.670	2.403	1.420	1.358	1.006	0.980	39.4	54.5
82.0	4.572	7.675	2.401	1.416	1.358	1.006	0.980	39.3	54.6
84.0	4.572	7.681	2.398	1.413	1.358	1.006	0.980	39.4	54.6
86.0	4.572	7.686	2.397	1.411	1.358	1.006	0.980	39.4	54.7
88.0	4.573	7.691	2.395	1.410	1.358	1.006	0.980	39.5	54.7
90.0	4.573	7.696	2.394	1.409	1.358	1.006	0.980	39.5	54.8
92.0	4.573	7.700	2.394	1.409	1.358	1.006	0.980	39.6	54.8
94.0	4.573	7.704	2.394	1.409	1.358	1.006	0.980	39.7	54.9
96.0	4.573	7.708	2.394	1.410	1.358	1.006	0.980	39.8	54.9
98.0	4.573	7.712	2.394	1.411	1.358	1.006	0.980	39.8	55.0

.CONTD

TIME	C1	C2	B1	B2	SI	O1	O2	L1	L2
100.0	4.573	7.714	2.395	1.412	1.358	1.006	0.980	39.9	55.0
102.0	4.573	7.717	2.396	1.413	1.358	1.006	0.980	40.0	55.0
104.0	4.573	7.719	2.397	1.415	1.358	1.006	0.980	40.0	55.1
106.0	4.573	7.721	2.397	1.416	1.358	1.006	0.980	40.1	55.1
108.0	4.574	7.722	2.398	1.417	1.358	1.006	0.980	40.1	55.1
110.0	4.574	7.723	2.399	1.419	1.358	1.006	0.980	40.1	55.1
112.0	4.574	7.724	2.400	1.420	1.358	1.006	0.980	40.1	55.1
114.0	4.574	7.725	2.401	1.421	1.358	1.006	0.980	40.1	55.1
116.0	4.574	7.725	2.401	1.422	1.358	1.006	0.980	40.1	55.1
118.0	4.574	7.725	2.402	1.423	1.358	1.006	0.980	40.1	55.1
120.0	4.574	7.725	2.402	1.423	1.358	1.006	0.980	40.1	55.1
122.0	4.574	7.725	2.403	1.424	1.358	1.006	0.980	40.1	55.1
124.0	4.574	7.725	2.403	1.424	1.358	1.006	0.980	40.1	55.1
126.0	4.574	7.725	2.403	1.424	1.358	1.006	0.980	40.1	55.0
128.0	4.574	7.725	2.403	1.424	1.358	1.006	0.980	40.1	55.0
130.0	4.574	7.725	2.403	1.424	1.358	1.006	0.980	40.1	55.0
132.0	4.574	7.725	2.403	1.424	1.358	1.006	0.980	40.0	55.0
134.0	4.574	7.725	2.403	1.423	1.358	1.006	0.980	40.0	55.0
136.0	4.574	7.725	2.403	1.423	1.358	1.006	0.980	40.0	55.0
138.0	4.574	7.725	2.402	1.423	1.358	1.006	0.980	40.0	55.0
140.0	4.574	7.725	2.402	1.422	1.358	1.006	0.980	40.0	55.0
142.0	4.574	7.725	2.402	1.422	1.358	1.006	0.980	40.0	55.0
144.0	4.574	7.726	2.402	1.422	1.358	1.006	0.980	40.0	55.0
146.0	4.574	7.726	2.402	1.422	1.358	1.006	0.980	40.0	55.0
148.0	4.574	7.726	2.402	1.421	1.358	1.006	0.980	40.0	55.0
150.0	4.574	7.726	2.401	1.421	1.358	1.006	0.980	40.0	55.0
152.0	4.574	7.726	2.401	1.421	1.358	1.006	0.980	40.0	55.0
154.0	4.574	7.727	2.401	1.421	1.358	1.006	0.980	40.0	55.0
156.0	4.574	7.727	2.401	1.421	1.358	1.006	0.980	40.0	55.0
158.0	4.574	7.727	2.401	1.421	1.358	1.006	0.980	40.0	55.0
160.0	4.574	7.727	2.401	1.421	1.358	1.006	0.980	40.0	55.0
162.0	4.574	7.727	2.401	1.421	1.358	1.006	0.980	40.0	55.0
164.0	4.574	7.728	2.401	1.421	1.358	1.006	0.980	40.0	55.0
166.0	4.574	7.728	2.401	1.421	1.358	1.006	0.980	40.0	55.0
168.0	4.574	7.728	2.401	1.421	1.358	1.006	0.980	40.0	55.0
170.0	4.574	7.728	2.401	1.421	1.358	1.006	0.980	40.0	55.0
172.0	4.574	7.728	2.401	1.421	1.358	1.006	0.980	40.0	55.0
174.0	4.574	7.728	2.401	1.421	1.358	1.006	0.980	40.0	55.0
176.0	4.574	7.728	2.401	1.421	1.358	1.006	0.980	40.0	55.0
178.0	4.574	7.728	2.401	1.421	1.358	1.006	0.980	40.0	55.0
180.0	4.574	7.728	2.401	1.421	1.358	1.006	0.980	40.0	55.0

CALCULATED FINAL CONDITIONS
F= 3.408, B1= 2.401, B2= 1.421, CF= 0.03223, C1= 0.04574
C2= 0.07728, TF= 85.0, TS1= 214.1, T1= 191.0, SI= 1.358

..CONTD

TIME	C1	C2	B1	B2	S1	O1	O2	L1	L2
100.0	4.573	7.714	2.395	1.412	1.358	1.006	0.980	39.9	55.0
102.0	4.573	7.717	2.396	1.413	1.358	1.006	0.980	40.0	55.0
104.0	4.573	7.719	2.397	1.415	1.358	1.006	0.980	40.0	55.1
106.0	4.573	7.721	2.397	1.416	1.358	1.006	0.980	40.1	55.1
108.0	4.574	7.722	2.398	1.417	1.358	1.006	0.980	40.1	55.1
110.0	4.574	7.723	2.399	1.419	1.358	1.006	0.980	40.1	55.1
112.0	4.574	7.724	2.400	1.420	1.358	1.006	0.980	40.1	55.1
114.0	4.574	7.725	2.401	1.421	1.358	1.006	0.980	40.1	55.1
116.0	4.574	7.725	2.401	1.422	1.358	1.006	0.980	40.1	55.1
118.0	4.574	7.725	2.402	1.423	1.358	1.006	0.980	40.1	55.1
120.0	4.574	7.725	2.402	1.423	1.358	1.006	0.980	40.1	55.1
122.0	4.574	7.725	2.403	1.424	1.358	1.006	0.980	40.1	55.1
124.0	4.574	7.725	2.403	1.424	1.358	1.006	0.980	40.1	55.1
126.0	4.574	7.725	2.403	1.424	1.358	1.006	0.980	40.1	55.0
128.0	4.574	7.725	2.403	1.424	1.358	1.006	0.980	40.1	55.0
130.0	4.574	7.725	2.403	1.424	1.358	1.006	0.980	40.1	55.0
132.0	4.574	7.725	2.403	1.424	1.358	1.006	0.980	40.0	55.0
134.0	4.574	7.725	2.403	1.423	1.358	1.006	0.980	40.0	55.0
136.0	4.574	7.725	2.403	1.423	1.358	1.006	0.980	40.0	55.0
138.0	4.574	7.725	2.402	1.423	1.358	1.006	0.980	40.0	55.0
140.0	4.574	7.725	2.402	1.422	1.358	1.006	0.980	40.0	55.0
142.0	4.574	7.725	2.402	1.422	1.358	1.006	0.980	40.0	55.0
144.0	4.574	7.726	2.402	1.422	1.358	1.006	0.980	40.0	55.0
146.0	4.574	7.726	2.402	1.422	1.358	1.006	0.980	40.0	55.0
148.0	4.574	7.726	2.402	1.421	1.358	1.006	0.980	40.0	55.0
150.0	4.574	7.726	2.401	1.421	1.358	1.006	0.980	40.0	55.0
152.0	4.574	7.726	2.401	1.421	1.358	1.006	0.980	40.0	55.0
154.0	4.574	7.727	2.401	1.421	1.358	1.006	0.980	40.0	55.0
156.0	4.574	7.727	2.401	1.421	1.358	1.006	0.980	40.0	55.0
158.0	4.574	7.727	2.401	1.421	1.358	1.006	0.980	40.0	55.0
160.0	4.574	7.727	2.401	1.421	1.358	1.006	0.980	40.0	55.0
162.0	4.574	7.727	2.401	1.421	1.358	1.006	0.980	40.0	55.0
164.0	4.574	7.728	2.401	1.421	1.358	1.006	0.980	40.0	55.0
166.0	4.574	7.728	2.401	1.421	1.358	1.006	0.980	40.0	55.0
168.0	4.574	7.728	2.401	1.421	1.358	1.006	0.980	40.0	55.0
170.0	4.574	7.728	2.401	1.421	1.358	1.006	0.980	40.0	55.0
172.0	4.574	7.728	2.401	1.421	1.358	1.006	0.980	40.0	55.0
174.0	4.574	7.728	2.401	1.421	1.358	1.006	0.980	40.0	55.0
176.0	4.574	7.728	2.401	1.421	1.358	1.006	0.980	40.0	55.0
178.0	4.574	7.728	2.401	1.421	1.358	1.006	0.980	40.0	55.0
180.0	4.574	7.728	2.401	1.421	1.358	1.006	0.980	40.0	55.0

CALCULATED FINAL CONDITIONS

F= 3.408, B1= 2.401, B2= 1.421, CF= 0.03223, C1= 0.04574

C2= 0.07728, TF= 85.0, TS1= 214.1, T1= 191.0, S1= 1.358

EXPERIMENT 3

OPENLOOP RESPONSE TO A STEP UP IN STEAM RATE

INPUT DATA

INITIAL CONDITIONS
F= 3.310, B1= 2.230, B2= 1.160, CF= 0.02780, C1= 0.04090
C2= 0.07920, TF= 90.0, TS1= 223.0, T1= 199.0, T2= 150.0
HSI= 1175.5

FINAL CONDITIONS
F= 3.310, B1= 2.130, B2= 0.950, CF= 0.02780, C1= 0.04300
C2= 0.09500, TF= 90.0, TS1= 227.0, T1= 203.0, T2= 150.0
HSI= 1175.5

CALCULATED PARAMETERS
UA1= 60.47, UA2= 21.11, HL2= 13.18, HL3= 52.73

CONTROLLER SETTINGS
KL1= 80.0, KL2= 160.0, KC2= 130.0, TL1= 7.0, TL2= 6.0
TC2= 7.0, TDC2= 5.0

CALCULATED INITIAL CONDITIONS
F= 3.297, B1= 2.231, B2= 1.156, CF= 0.02775, C1= 0.04101
C2= 0.07916, TF= 90.0, TS1= 221.9, T1= 198.8, SI= 1.421

EXPERIMENT 3

OPENLOOP RESPONSE TO A STEP UP IN STEAM RATE

INPUT DATA

INITIAL CONDITIONS
F= 3.310, B1= 2.230, B2= 1.160, CF= 0.02780, C1= 0.04090
C2= 0.07920, TF= 90.0, TS1= 223.0, T1= 199.0, T2= 150.0
HS1= 1175.5

FINAL CONDITIONS
F= 3.310, B1= 2.130, B2= 0.950, CF= 0.02780, C1= 0.04300
C2= 0.09500, TF= 90.0, TS1= 227.0, T1= 203.0, T2= 150.0
HS1= 1175.5

CALCULATED PARAMETERS
UA1= 60.47, UA2= 21.11, HL2= 13.18, HL3= 52.73

CONTROLLER SETTINGS
KL1= 80.0, KL2= 160.0, KC2= 130.0, TL1= 7.0, TL2= 6.0
TC2= 7.0, TDC2= 5.0

CALCULATED INITIAL CONDITIONS
F= 3.297, B1= 2.231, B2= 1.156, CF= 0.02775, C1= 0.04101
C2= 0.07916, TF= 90.0, TS1= 221.9, T1= 198.8, S1= 1.421

TIME	C1	C2	B1	B2	SI	O1	O2	L1	L2
-2.0	4.101	7.916	2.231	1.156	1.421	1.066	1.075	40.0	55.0
-0.0	4.101	7.916	2.231	1.156	1.421	1.066	1.075	40.0	55.0
2.0	4.109	7.937	2.224	1.146	1.539	1.136	1.142	39.6	54.6
4.0	4.125	7.987	2.207	1.120	1.539	1.156	1.166	38.9	53.9
6.0	4.142	8.048	2.188	1.088	1.539	1.161	1.172	38.3	53.1
8.0	4.158	8.114	2.170	1.053	1.539	1.163	1.172	37.9	52.4
10.0	4.172	8.184	2.152	1.020	1.539	1.163	1.172	37.6	52.0
12.0	4.185	8.255	2.137	0.988	1.539	1.163	1.171	37.5	51.6
14.0	4.196	8.328	2.124	0.959	1.539	1.163	1.170	37.5	51.5
16.0	4.206	8.401	2.113	0.935	1.539	1.163	1.170	37.7	51.5
18.0	4.215	8.472	2.106	0.914	1.539	1.163	1.170	37.9	51.7
20.0	4.223	8.542	2.101	0.898	1.539	1.163	1.169	38.2	52.0
22.0	4.230	8.608	2.099	0.887	1.539	1.163	1.169	38.6	52.4
24.0	4.236	8.672	2.099	0.880	1.539	1.163	1.169	38.9	52.8
26.0	4.242	8.732	2.101	0.878	1.539	1.163	1.169	39.3	53.4
28.0	4.247	8.787	2.104	0.880	1.539	1.163	1.169	39.6	53.9
30.0	4.251	8.838	2.109	0.886	1.539	1.163	1.170	39.9	54.5
32.0	4.255	8.885	2.113	0.895	1.539	1.163	1.170	40.1	55.0
34.0	4.259	8.928	2.118	0.906	1.539	1.163	1.170	40.3	55.5
36.0	4.262	8.967	2.123	0.919	1.539	1.163	1.170	40.4	55.8
38.0	4.265	9.002	2.127	0.932	1.539	1.163	1.171	40.5	56.1
40.0	4.267	9.034	2.131	0.945	1.539	1.163	1.171	40.6	56.4
42.0	4.269	9.063	2.135	0.958	1.539	1.163	1.171	40.6	56.5
44.0	4.271	9.090	2.137	0.969	1.539	1.163	1.171	40.6	56.5
46.0	4.273	9.114	2.139	0.978	1.539	1.163	1.171	40.5	56.4
48.0	4.275	9.136	2.141	0.985	1.539	1.163	1.171	40.5	56.3
50.0	4.276	9.157	2.142	0.990	1.539	1.163	1.171	40.4	56.1
52.0	4.277	9.176	2.142	0.993	1.539	1.163	1.171	40.3	55.9
54.0	4.279	9.194	2.142	0.993	1.539	1.163	1.171	40.2	55.7
56.0	4.280	9.212	2.141	0.992	1.539	1.163	1.171	40.1	55.4
58.0	4.280	9.228	2.140	0.989	1.539	1.163	1.171	40.1	55.2
60.0	4.281	9.244	2.139	0.986	1.539	1.163	1.171	40.0	55.0
62.0	4.282	9.259	2.138	0.982	1.539	1.163	1.171	39.9	54.8
64.0	4.283	9.274	2.137	0.977	1.539	1.163	1.171	39.9	54.7
66.0	4.283	9.288	2.136	0.972	1.539	1.163	1.171	39.9	54.6
68.0	4.284	9.301	2.135	0.968	1.539	1.163	1.171	39.9	54.6
70.0	4.284	9.314	2.134	0.964	1.539	1.163	1.171	39.9	54.5
72.0	4.284	9.327	2.133	0.961	1.539	1.163	1.171	39.9	54.5
74.0	4.285	9.339	2.133	0.958	1.539	1.163	1.171	39.9	54.6
76.0	4.285	9.350	2.132	0.956	1.539	1.163	1.171	39.9	54.6
78.0	4.285	9.361	2.132	0.955	1.539	1.163	1.171	39.9	54.7
80.0	4.286	9.371	2.132	0.954	1.539	1.163	1.171	39.9	54.7
82.0	4.286	9.380	2.132	0.954	1.539	1.163	1.171	39.9	54.8
84.0	4.286	9.389	2.132	0.954	1.539	1.163	1.171	40.0	54.9
86.0	4.286	9.397	2.132	0.955	1.539	1.163	1.171	40.0	54.9
88.0	4.286	9.405	2.132	0.956	1.539	1.163	1.171	40.0	55.0
90.0	4.287	9.412	2.133	0.958	1.539	1.163	1.171	40.0	55.1
92.0	4.287	9.418	2.133	0.959	1.539	1.163	1.171	40.0	55.1
94.0	4.287	9.424	2.133	0.960	1.539	1.163	1.171	40.0	55.1
96.0	4.287	9.429	2.133	0.961	1.539	1.163	1.171	40.0	55.1
98.0	4.287	9.434	2.134	0.963	1.539	1.163	1.171	40.0	55.1

TIME	C1	C2	B1	B2	S1	O1	O2	L1	L2
-2.0	4.101	7.916	2.231	1.156	1.421	1.066	1.075	40.0	55.0
-0.0	4.101	7.916	2.231	1.156	1.421	1.066	1.075	40.0	55.0
2.0	4.109	7.937	2.224	1.146	1.539	1.136	1.142	39.6	54.6
4.0	4.125	7.987	2.207	1.120	1.539	1.156	1.166	38.9	53.9
6.0	4.142	8.048	2.188	1.088	1.539	1.161	1.172	38.3	53.1
8.0	4.158	8.114	2.170	1.053	1.539	1.163	1.172	37.9	52.4
10.0	4.172	8.184	2.152	1.020	1.539	1.163	1.172	37.6	52.0
12.0	4.185	8.255	2.137	0.988	1.539	1.163	1.171	37.5	51.6
14.0	4.196	8.328	2.124	0.959	1.539	1.163	1.170	37.5	51.5
16.0	4.206	8.401	2.113	0.935	1.539	1.163	1.170	37.7	51.5
18.0	4.215	8.472	2.106	0.914	1.539	1.163	1.170	37.9	51.7
20.0	4.223	8.542	2.101	0.898	1.539	1.163	1.169	38.2	52.0
22.0	4.230	8.608	2.099	0.887	1.539	1.163	1.169	38.6	52.4
24.0	4.236	8.672	2.099	0.880	1.539	1.163	1.169	38.9	52.8
26.0	4.242	8.732	2.101	0.878	1.539	1.163	1.169	39.3	53.4
28.0	4.247	8.787	2.104	0.880	1.539	1.163	1.169	39.6	53.9
30.0	4.251	8.838	2.109	0.886	1.539	1.163	1.170	39.9	54.5
32.0	4.255	8.885	2.113	0.895	1.539	1.163	1.170	40.1	55.0
34.0	4.259	8.928	2.118	0.906	1.539	1.163	1.170	40.3	55.5
36.0	4.262	8.967	2.123	0.919	1.539	1.163	1.170	40.4	55.8
38.0	4.265	9.002	2.127	0.932	1.539	1.163	1.171	40.5	56.1
40.0	4.267	9.034	2.131	0.945	1.539	1.163	1.171	40.6	56.4
42.0	4.269	9.063	2.135	0.958	1.539	1.163	1.171	40.6	56.5
44.0	4.271	9.090	2.137	0.969	1.539	1.163	1.171	40.6	56.5
46.0	4.273	9.114	2.139	0.978	1.539	1.163	1.171	40.5	56.4
48.0	4.275	9.136	2.141	0.985	1.539	1.163	1.171	40.5	56.3
50.0	4.276	9.157	2.142	0.990	1.539	1.163	1.171	40.4	56.1
52.0	4.277	9.176	2.142	0.993	1.539	1.163	1.171	40.3	55.9
54.0	4.279	9.194	2.142	0.993	1.539	1.163	1.171	40.2	55.7
56.0	4.280	9.212	2.141	0.992	1.539	1.163	1.171	40.1	55.4
58.0	4.280	9.228	2.140	0.989	1.539	1.163	1.171	40.1	55.2
60.0	4.281	9.244	2.139	0.986	1.539	1.163	1.171	40.0	55.0
62.0	4.282	9.259	2.138	0.982	1.539	1.163	1.171	39.9	54.8
64.0	4.283	9.274	2.137	0.977	1.539	1.163	1.171	39.9	54.7
66.0	4.283	9.288	2.136	0.972	1.539	1.163	1.171	39.9	54.6
68.0	4.284	9.301	2.135	0.968	1.539	1.163	1.171	39.9	54.6
70.0	4.284	9.314	2.134	0.964	1.539	1.163	1.171	39.9	54.5
72.0	4.284	9.327	2.133	0.961	1.539	1.163	1.171	39.9	54.5
74.0	4.285	9.339	2.133	0.958	1.539	1.163	1.171	39.9	54.6
76.0	4.285	9.350	2.132	0.956	1.539	1.163	1.171	39.9	54.6
78.0	4.285	9.361	2.132	0.955	1.539	1.163	1.171	39.9	54.7
80.0	4.286	9.371	2.132	0.954	1.539	1.163	1.171	39.9	54.7
82.0	4.286	9.380	2.132	0.954	1.539	1.163	1.171	39.9	54.8
84.0	4.286	9.389	2.132	0.954	1.539	1.163	1.171	40.0	54.9
86.0	4.286	9.397	2.132	0.955	1.539	1.163	1.171	40.0	54.9
88.0	4.286	9.405	2.132	0.956	1.539	1.163	1.171	40.0	55.0
90.0	4.287	9.412	2.133	0.958	1.539	1.163	1.171	40.0	55.1
92.0	4.287	9.418	2.133	0.959	1.539	1.163	1.171	40.0	55.1
94.0	4.287	9.424	2.133	0.960	1.539	1.163	1.171	40.0	55.1
96.0	4.287	9.429	2.133	0.961	1.539	1.163	1.171	40.0	55.1
98.0	4.287	9.434	2.134	0.963	1.539	1.163	1.171	40.0	55.1

.1.CONTD

TIME	C1	C2	B1	B2	SI	O1	O2	L1	L2
100.0	4.287	9.439	2.134	0.963	1.539	1.163	1.171	40.0	55.1
102.0	4.287	9.443	2.134	0.964	1.539	1.163	1.171	40.0	55.1
104.0	4.287	9.447	2.134	0.965	1.539	1.163	1.171	40.0	55.1
106.0	4.287	9.451	2.134	0.965	1.539	1.163	1.171	40.0	55.1
108.0	4.287	9.454	2.134	0.965	1.539	1.163	1.171	40.0	55.1
110.0	4.287	9.457	2.134	0.965	1.539	1.163	1.171	40.0	55.1
112.0	4.287	9.460	2.134	0.965	1.539	1.163	1.171	40.0	55.0
114.0	4.288	9.463	2.134	0.965	1.539	1.163	1.171	40.0	55.0
116.0	4.288	9.465	2.134	0.965	1.539	1.163	1.171	40.0	55.0
118.0	4.288	9.468	2.134	0.964	1.539	1.163	1.171	40.0	55.0
120.0	4.288	9.470	2.134	0.964	1.539	1.163	1.171	40.0	55.0
122.0	4.288	9.472	2.134	0.964	1.539	1.163	1.171	40.0	55.0
124.0	4.288	9.474	2.134	0.963	1.539	1.163	1.171	40.0	55.0
126.0	4.288	9.476	2.134	0.963	1.539	1.163	1.171	40.0	55.0
128.0	4.288	9.478	2.134	0.963	1.539	1.163	1.171	40.0	55.0
130.0	4.288	9.479	2.134	0.963	1.539	1.163	1.171	40.0	55.0
132.0	4.288	9.481	2.134	0.962	1.539	1.163	1.171	40.0	55.0
134.0	4.288	9.482	2.134	0.962	1.539	1.163	1.171	40.0	55.0
136.0	4.288	9.484	2.134	0.962	1.539	1.163	1.171	40.0	55.0
138.0	4.288	9.485	2.134	0.962	1.539	1.163	1.171	40.0	55.0
140.0	4.288	9.486	2.134	0.962	1.539	1.163	1.171	40.0	55.0
142.0	4.288	9.487	2.134	0.962	1.539	1.163	1.171	40.0	55.0
144.0	4.288	9.488	2.134	0.962	1.539	1.163	1.171	40.0	55.0
146.0	4.288	9.489	2.134	0.963	1.539	1.163	1.171	40.0	55.0
148.0	4.288	9.490	2.134	0.963	1.539	1.163	1.171	40.0	55.0
150.0	4.288	9.491	2.134	0.963	1.539	1.163	1.171	40.0	55.0
152.0	4.288	9.492	2.134	0.963	1.539	1.163	1.171	40.0	55.0
154.0	4.288	9.493	2.134	0.963	1.539	1.163	1.171	40.0	55.0
156.0	4.288	9.493	2.134	0.963	1.539	1.163	1.171	40.0	55.0
158.0	4.288	9.494	2.134	0.963	1.539	1.163	1.171	40.0	55.0
160.0	4.288	9.494	2.134	0.963	1.539	1.163	1.171	40.0	55.0
162.0	4.288	9.495	2.134	0.963	1.539	1.163	1.171	40.0	55.0
164.0	4.288	9.495	2.134	0.963	1.539	1.163	1.171	40.0	55.0
166.0	4.288	9.496	2.134	0.963	1.539	1.163	1.171	40.0	55.0
168.0	4.288	9.496	2.134	0.963	1.539	1.163	1.171	40.0	55.0
170.0	4.288	9.497	2.134	0.963	1.539	1.163	1.171	40.0	55.0
172.0	4.288	9.497	2.134	0.963	1.539	1.163	1.171	40.0	55.0
174.0	4.288	9.497	2.134	0.963	1.539	1.163	1.171	40.0	55.0
176.0	4.288	9.498	2.134	0.963	1.539	1.163	1.171	40.0	55.0
178.0	4.288	9.498	2.134	0.963	1.539	1.163	1.171	40.0	55.0
180.0	4.288	9.498	2.134	0.963	1.539	1.163	1.171	40.0	55.0

CALCULATED FINAL CONDITIONS
F= 3.297, B1= 2.134, B2= 0.963, CF= 0.02775, C1= 0.04288
C2= 0.09498, TF= 90.0, TS1= 228.0, T1= 203.2, SI= 1.539

..CONTD

TIME	C1	C2	B1	B2	S1	O1	O2	L1	L2
100.0	4.287	9.439	2.134	0.963	1.539	1.163	1.171	40.0	55.1
102.0	4.287	9.443	2.134	0.964	1.539	1.163	1.171	40.0	55.1
104.0	4.287	9.447	2.134	0.965	1.539	1.163	1.171	40.0	55.1
106.0	4.287	9.451	2.134	0.965	1.539	1.163	1.171	40.0	55.1
108.0	4.287	9.454	2.134	0.965	1.539	1.163	1.171	40.0	55.1
110.0	4.287	9.457	2.134	0.965	1.539	1.163	1.171	40.0	55.1
112.0	4.287	9.460	2.134	0.965	1.539	1.163	1.171	40.0	55.0
114.0	4.288	9.463	2.134	0.965	1.539	1.163	1.171	40.0	55.0
116.0	4.288	9.465	2.134	0.965	1.539	1.163	1.171	40.0	55.0
118.0	4.288	9.468	2.134	0.964	1.539	1.163	1.171	40.0	55.0
120.0	4.288	9.470	2.134	0.964	1.539	1.163	1.171	40.0	55.0
122.0	4.288	9.472	2.134	0.964	1.539	1.163	1.171	40.0	55.0
124.0	4.288	9.474	2.134	0.963	1.539	1.163	1.171	40.0	55.0
126.0	4.288	9.476	2.134	0.963	1.539	1.163	1.171	40.0	55.0
128.0	4.288	9.478	2.134	0.963	1.539	1.163	1.171	40.0	55.0
130.0	4.288	9.479	2.134	0.963	1.539	1.163	1.171	40.0	55.0
132.0	4.288	9.481	2.134	0.962	1.539	1.163	1.171	40.0	55.0
134.0	4.288	9.482	2.134	0.962	1.539	1.163	1.171	40.0	55.0
136.0	4.288	9.484	2.134	0.962	1.539	1.163	1.171	40.0	55.0
138.0	4.288	9.485	2.134	0.962	1.539	1.163	1.171	40.0	55.0
140.0	4.288	9.486	2.134	0.962	1.539	1.163	1.171	40.0	55.0
142.0	4.288	9.487	2.134	0.962	1.539	1.163	1.171	40.0	55.0
144.0	4.288	9.488	2.134	0.962	1.539	1.163	1.171	40.0	55.0
146.0	4.288	9.489	2.134	0.963	1.539	1.163	1.171	40.0	55.0
148.0	4.288	9.490	2.134	0.963	1.539	1.163	1.171	40.0	55.0
150.0	4.288	9.491	2.134	0.963	1.539	1.163	1.171	40.0	55.0
152.0	4.288	9.492	2.134	0.963	1.539	1.163	1.171	40.0	55.0
154.0	4.288	9.493	2.134	0.963	1.539	1.163	1.171	40.0	55.0
156.0	4.288	9.493	2.134	0.963	1.539	1.163	1.171	40.0	55.0
158.0	4.288	9.494	2.134	0.963	1.539	1.163	1.171	40.0	55.0
160.0	4.288	9.494	2.134	0.963	1.539	1.163	1.171	40.0	55.0
162.0	4.288	9.495	2.134	0.963	1.539	1.163	1.171	40.0	55.0
164.0	4.288	9.495	2.134	0.963	1.539	1.163	1.171	40.0	55.0
166.0	4.288	9.496	2.134	0.963	1.539	1.163	1.171	40.0	55.0
168.0	4.288	9.496	2.134	0.963	1.539	1.163	1.171	40.0	55.0
170.0	4.288	9.497	2.134	0.963	1.539	1.163	1.171	40.0	55.0
172.0	4.288	9.497	2.134	0.963	1.539	1.163	1.171	40.0	55.0
174.0	4.288	9.497	2.134	0.963	1.539	1.163	1.171	40.0	55.0
176.0	4.288	9.498	2.134	0.963	1.539	1.163	1.171	40.0	55.0
178.0	4.288	9.498	2.134	0.963	1.539	1.163	1.171	40.0	55.0
180.0	4.288	9.498	2.134	0.963	1.539	1.163	1.171	40.0	55.0

CALCULATED FINAL CONDITIONS

F= 3.297, B1= 2.134, B2= 0.963, CF= 0.02775, C1= 0.04288

C2= 0.09498, TF= 90.0, TS1= 228.0, T1= 203.2, S1= 1.539

EXPERIMENT 4

CLOSED LOOP RESPONSE TO A STEP UP IN FEED RATE

INPUT DATA

INITIAL CONDITIONS
F= 2.430, B1= 1.690, B2= 0.980, CF= 0.03020, C1= 0.04340
C2= 0.07510, TF= 88.5, TS1= 201.0, T1= 184.0, T2= 149.5
HSI= 1175.1

FINAL CONDITIONS
F= 2.930, B1= 2.050, B2= 1.180, CF= 0.03020, C1= 0.04320
C2= 0.07510, TF= 93.0, TS1= 211.0, T1= 190.0, T2= 149.5
HSI= 1175.1

CALCULATED PARAMETERS
UA1= 55.57, UA2= 20.92, HL2= 13.98, HL3= 55.91

CONTROLLER SETTINGS
KL1= 80.0, KL2= 175.0, KC2= 130.0, TL1= 6.0, TL2= 6.0
TC2= 7.0, TDC2= 5.0

CALCULATED INITIAL CONDITIONS
F= 2.431, B1= 1.691, B2= 0.978, CF= 0.03021, C1= 0.04344
C2= 0.07507, TF= 90.8, TS1= 201.0, T1= 183.8, SI= 0.951

EXPERIMENT 4

CLOSED LOOP RESPONSE TO A STEP UP IN FEED RATE

INPUT DATA

INITIAL CONDITIONS
F= 2.430, B1= 1.690, B2= 0.980, CF= 0.03020, C1= 0.04340
C2= 0.07510, TF= 88.5, TS1= 201.0, T1= 184.0, T2= 149.5
HS1= 1175.1

FINAL CONDITIONS
F= 2.930, B1= 2.050, B2= 1.180, CF= 0.03020, C1= 0.04320
C2= 0.07510, TF= 93.0, TS1= 211.0, T1= 190.0, T2= 149.5
HS1= 1175.1

CALCULATED PARAMETERS
UA1= 55.57, UA2= 20.92, HL2= 13.98, HL3= 55.91

CONTROLLER SETTINGS
KL1= 80.0, KL2= 175.0, KC2= 130.0, TL1= 6.0, TL2= 6.0
TC2= 7.0, TDC2= 5.0

CALCULATED INITIAL CONDITIONS
F= 2.431, B1= 1.691, B2= 0.978, CF= 0.03021, C1= 0.04344
C2= 0.07507, TF= 90.8, TS1= 201.0, T1= 183.8, S1= 0.951

TIME	C1	C2	B1	B2	SI	O1	O2	L1	L2
-2.0	4.344	7.507	1.691	0.978	0.951	0.741	0.712	40.0	55.0
-0.0	4.344	7.507	1.691	0.978	0.951	0.741	0.712	40.0	55.0
2.0	4.311	7.489	1.807	0.992	0.968	0.719	0.695	44.2	55.6
4.0	4.278	7.440	1.929	1.036	0.986	0.723	0.702	47.7	57.2
6.0	4.251	7.373	2.038	1.107	1.005	0.736	0.718	50.0	59.4
8.0	4.230	7.296	2.128	1.201	1.026	0.752	0.737	51.0	61.5
10.0	4.214	7.217	2.199	1.308	1.047	0.769	0.758	51.1	63.1
12.0	4.203	7.141	2.251	1.418	1.068	0.787	0.779	50.3	64.1
14.0	4.198	7.073	2.285	1.515	1.090	0.805	0.799	49.0	64.2
16.0	4.196	7.016	2.300	1.588	1.111	0.824	0.819	47.1	63.5
18.0	4.199	6.971	2.300	1.628	1.131	0.842	0.838	45.1	62.1
20.0	4.204	6.940	2.285	1.633	1.150	0.859	0.856	42.9	60.2
22.0	4.213	6.925	2.257	1.605	1.168	0.875	0.872	40.8	58.0
24.0	4.224	6.926	2.220	1.552	1.183	0.889	0.886	38.8	55.7
26.0	4.237	6.942	2.177	1.481	1.196	0.902	0.897	37.1	53.6
28.0	4.252	6.973	2.129	1.399	1.207	0.912	0.906	35.8	51.6
30.0	4.267	7.018	2.081	1.313	1.215	0.921	0.914	34.9	50.0
32.0	4.282	7.075	2.035	1.228	1.221	0.927	0.918	34.4	48.7
34.0	4.296	7.140	1.993	1.148	1.224	0.932	0.921	34.3	47.7
36.0	4.310	7.212	1.959	1.076	1.225	0.934	0.922	34.5	47.1
38.0	4.323	7.288	1.933	1.013	1.224	0.934	0.922	35.0	46.9
40.0	4.334	7.364	1.917	0.962	1.222	0.933	0.920	35.8	47.1
42.0	4.344	7.438	1.909	0.922	1.218	0.931	0.918	36.7	47.6
44.0	4.352	7.506	1.909	0.895	1.213	0.927	0.914	37.7	48.5
46.0	4.359	7.566	1.917	0.880	1.207	0.923	0.910	38.6	49.6
48.0	4.363	7.618	1.929	0.877	1.201	0.918	0.906	39.5	51.0
50.0	4.366	7.660	1.946	0.886	1.195	0.913	0.901	40.3	52.6
52.0	4.368	7.692	1.965	0.907	1.188	0.908	0.896	41.0	54.3
54.0	4.368	7.714	1.985	0.939	1.182	0.902	0.891	41.5	55.9
56.0	4.367	7.726	2.005	0.980	1.175	0.897	0.886	41.9	57.4
58.0	4.365	7.731	2.024	1.029	1.169	0.891	0.882	42.2	58.7
60.0	4.362	7.728	2.041	1.082	1.164	0.886	0.877	42.3	59.7
62.0	4.358	7.718	2.056	1.136	1.159	0.882	0.873	42.2	60.4
64.0	4.354	7.704	2.068	1.188	1.155	0.878	0.869	42.1	60.7
66.0	4.349	7.687	2.078	1.234	1.151	0.875	0.866	42.0	60.6
68.0	4.344	7.666	2.085	1.271	1.149	0.872	0.863	41.7	60.2
70.0	4.339	7.644	2.090	1.299	1.147	0.870	0.861	41.4	59.6
72.0	4.334	7.621	2.093	1.316	1.145	0.868	0.860	41.1	58.8
74.0	4.330	7.598	2.094	1.323	1.144	0.867	0.858	40.8	58.0
76.0	4.326	7.576	2.092	1.321	1.144	0.866	0.858	40.6	57.1
78.0	4.322	7.555	2.090	1.313	1.144	0.866	0.857	40.3	56.2
80.0	4.318	7.535	2.087	1.299	1.144	0.866	0.857	40.1	55.4
82.0	4.315	7.518	2.082	1.283	1.145	0.866	0.857	39.9	54.8
84.0	4.312	7.503	2.078	1.265	1.146	0.867	0.858	39.7	54.3
86.0	4.310	7.490	2.073	1.246	1.148	0.868	0.859	39.6	53.9
88.0	4.308	7.479	2.068	1.228	1.149	0.869	0.860	39.5	53.6
90.0	4.307	7.471	2.064	1.212	1.150	0.871	0.861	39.5	53.5
92.0	4.306	7.465	2.060	1.198	1.152	0.872	0.862	39.4	53.4
94.0	4.305	7.460	2.057	1.186	1.154	0.873	0.863	39.4	53.5
96.0	4.305	7.457	2.054	1.176	1.155	0.874	0.865	39.5	53.6
98.0	4.305	7.456	2.051	1.169	1.157	0.876	0.866	39.5	53.7

TIME	C1	C2	B1	B2	S1	O1	O2	L1	L2
-2.0	4.344	7.507	1.691	0.978	0.951	0.741	0.712	40.0	55.0
-0.0	4.344	7.507	1.691	0.978	0.951	0.741	0.712	40.0	55.0
2.0	4.311	7.489	1.807	0.992	0.968	0.719	0.695	44.2	55.6
4.0	4.278	7.440	1.929	1.036	0.986	0.723	0.702	47.7	57.2
6.0	4.251	7.373	2.038	1.107	1.005	0.736	0.718	50.0	59.4
8.0	4.230	7.296	2.128	1.201	1.026	0.752	0.737	51.0	61.5
10.0	4.214	7.217	2.199	1.308	1.047	0.769	0.758	51.1	63.1
12.0	4.203	7.141	2.251	1.418	1.068	0.787	0.779	50.3	64.1
14.0	4.198	7.073	2.285	1.515	1.090	0.805	0.799	49.0	64.2
16.0	4.196	7.016	2.300	1.588	1.111	0.824	0.819	47.1	63.5
18.0	4.199	6.971	2.300	1.628	1.131	0.842	0.838	45.1	62.1
20.0	4.204	6.940	2.285	1.633	1.150	0.859	0.856	42.9	60.2
22.0	4.213	6.925	2.257	1.605	1.168	0.875	0.872	40.8	58.0
24.0	4.224	6.926	2.220	1.552	1.183	0.889	0.886	38.8	55.7
26.0	4.237	6.942	2.177	1.481	1.196	0.902	0.897	37.1	53.6
28.0	4.252	6.973	2.129	1.399	1.207	0.912	0.906	35.8	51.6
30.0	4.267	7.018	2.081	1.313	1.215	0.921	0.914	34.9	50.0
32.0	4.282	7.075	2.035	1.228	1.221	0.927	0.918	34.4	48.7
34.0	4.296	7.140	1.993	1.148	1.224	0.932	0.921	34.3	47.7
36.0	4.310	7.212	1.959	1.076	1.225	0.934	0.922	34.5	47.1
38.0	4.323	7.288	1.933	1.013	1.224	0.934	0.922	35.0	46.9
40.0	4.334	7.364	1.917	0.962	1.222	0.933	0.920	35.8	47.1
42.0	4.344	7.438	1.909	0.922	1.218	0.931	0.918	36.7	47.6
44.0	4.352	7.506	1.909	0.895	1.213	0.927	0.914	37.7	48.5
46.0	4.359	7.566	1.917	0.880	1.207	0.923	0.910	38.6	49.6
48.0	4.363	7.618	1.929	0.877	1.201	0.918	0.906	39.5	51.0
50.0	4.366	7.660	1.946	0.886	1.195	0.913	0.901	40.3	52.6
52.0	4.368	7.692	1.965	0.907	1.188	0.908	0.896	41.0	54.3
54.0	4.368	7.714	1.985	0.939	1.182	0.902	0.891	41.5	55.9
56.0	4.367	7.726	2.005	0.980	1.175	0.897	0.886	41.9	57.4
58.0	4.365	7.731	2.024	1.029	1.169	0.891	0.882	42.2	58.7
60.0	4.362	7.728	2.041	1.082	1.164	0.886	0.877	42.3	59.7
62.0	4.358	7.718	2.056	1.136	1.159	0.882	0.873	42.2	60.4
64.0	4.354	7.704	2.068	1.188	1.155	0.878	0.869	42.1	60.7
66.0	4.349	7.687	2.078	1.234	1.151	0.875	0.866	42.0	60.6
68.0	4.344	7.666	2.085	1.271	1.149	0.872	0.863	41.7	60.2
70.0	4.339	7.644	2.090	1.299	1.147	0.870	0.861	41.4	59.6
72.0	4.334	7.621	2.093	1.316	1.145	0.868	0.860	41.1	58.8
74.0	4.330	7.598	2.094	1.323	1.144	0.867	0.858	40.8	58.0
76.0	4.326	7.576	2.092	1.321	1.144	0.866	0.858	40.6	57.1
78.0	4.322	7.555	2.090	1.313	1.144	0.866	0.857	40.3	56.2
80.0	4.318	7.535	2.087	1.299	1.144	0.866	0.857	40.1	55.4
82.0	4.315	7.518	2.082	1.283	1.145	0.866	0.857	39.9	54.8
84.0	4.312	7.503	2.078	1.265	1.146	0.867	0.858	39.7	54.3
86.0	4.310	7.490	2.073	1.246	1.148	0.868	0.859	39.6	53.9
88.0	4.308	7.479	2.068	1.228	1.149	0.869	0.860	39.5	53.6
90.0	4.307	7.471	2.064	1.212	1.150	0.871	0.861	39.5	53.5
92.0	4.306	7.465	2.060	1.198	1.152	0.872	0.862	39.4	53.4
94.0	4.305	7.460	2.057	1.186	1.154	0.873	0.863	39.4	53.5
96.0	4.305	7.457	2.054	1.176	1.155	0.874	0.865	39.5	53.6
98.0	4.305	7.456	2.051	1.169	1.157	0.876	0.866	39.5	53.7

..CONTD

TIME	C1	C2	B1	B2	SI	O1	O2	L1	L2
100.0	4.306	7.456	2.049	1.163	1.158	0.877	0.867	39.6	53.9
102.0	4.306	7.458	2.048	1.160	1.159	0.878	0.868	39.6	54.1
104.0	4.307	7.460	2.046	1.158	1.161	0.879	0.869	39.7	54.3
106.0	4.308	7.462	2.046	1.158	1.162	0.880	0.870	39.7	54.5
108.0	4.309	7.466	2.045	1.158	1.163	0.881	0.871	39.8	54.6
110.0	4.310	7.469	2.045	1.160	1.163	0.882	0.872	39.9	54.8
112.0	4.311	7.473	2.045	1.161	1.164	0.883	0.873	39.9	54.9
114.0	4.312	7.477	2.045	1.163	1.165	0.883	0.873	39.9	55.0
116.0	4.314	7.482	2.045	1.166	1.165	0.884	0.874	40.0	55.1
118.0	4.315	7.486	2.046	1.168	1.165	0.884	0.874	40.0	55.1
120.0	4.316	7.490	2.046	1.170	1.166	0.884	0.875	40.0	55.2
122.0	4.317	7.494	2.046	1.171	1.166	0.884	0.875	40.0	55.2
124.0	4.318	7.498	2.046	1.172	1.166	0.884	0.875	40.0	55.2
126.0	4.319	7.501	2.047	1.173	1.166	0.884	0.875	40.0	55.2
128.0	4.319	7.505	2.047	1.174	1.165	0.884	0.875	40.0	55.1
130.0	4.320	7.508	2.047	1.175	1.165	0.884	0.875	40.0	55.1
132.0	4.320	7.510	2.047	1.175	1.165	0.884	0.874	40.0	55.1
134.0	4.321	7.513	2.048	1.175	1.165	0.884	0.874	40.0	55.1
136.0	4.321	7.515	2.048	1.175	1.164	0.883	0.874	40.0	55.1
138.0	4.321	7.517	2.048	1.176	1.164	0.883	0.873	40.0	55.1
140.0	4.321	7.518	2.049	1.176	1.163	0.883	0.873	40.0	55.0
142.0	4.321	7.519	2.049	1.176	1.163	0.882	0.873	40.0	55.0
144.0	4.321	7.519	2.049	1.177	1.162	0.882	0.872	40.0	55.0
146.0	4.321	7.520	2.050	1.177	1.162	0.882	0.872	40.1	55.1
148.0	4.321	7.520	2.050	1.178	1.162	0.881	0.872	40.1	55.1
150.0	4.321	7.519	2.051	1.178	1.161	0.881	0.871	40.1	55.1
152.0	4.321	7.519	2.051	1.179	1.161	0.881	0.871	40.1	55.1
154.0	4.320	7.518	2.051	1.180	1.161	0.880	0.871	40.1	55.1
156.0	4.320	7.517	2.052	1.181	1.161	0.880	0.871	40.1	55.1
158.0	4.320	7.516	2.052	1.181	1.160	0.880	0.871	40.0	55.1
160.0	4.319	7.515	2.052	1.182	1.160	0.880	0.870	40.0	55.1
162.0	4.319	7.514	2.052	1.182	1.160	0.880	0.870	40.0	55.1
164.0	4.319	7.512	2.052	1.183	1.160	0.880	0.870	40.0	55.1
166.0	4.318	7.511	2.052	1.183	1.160	0.880	0.870	40.0	55.1
168.0	4.318	7.510	2.053	1.183	1.160	0.880	0.870	40.0	55.1
170.0	4.318	7.509	2.052	1.184	1.160	0.880	0.870	40.0	55.0
172.0	4.318	7.508	2.052	1.183	1.160	0.880	0.870	40.0	55.0
174.0	4.317	7.507	2.052	1.183	1.160	0.880	0.870	40.0	55.0
176.0	4.317	7.506	2.052	1.183	1.160	0.880	0.870	40.0	55.0
178.0	4.317	7.505	2.052	1.183	1.161	0.880	0.870	40.0	55.0
180.0	4.317	7.504	2.052	1.182	1.161	0.880	0.870	40.0	55.0

CALCULATED FINAL CONDITIONS
F= 2.932, B1= 2.052, B2= 1.182, CF= 0.03021, C1= 0.04317
C2= 0.07504, TF= 90.8, TS1= 211.0, T1= 190.2, SI= 1.161

..CONTD

TIME	C1	C2	B1	B2	S1	O1	O2	L1	L2
100.0	4.306	7.456	2.049	1.163	1.158	0.877	0.867	39.6	53.9
102.0	4.306	7.458	2.048	1.160	1.159	0.878	0.868	39.6	54.1
104.0	4.307	7.460	2.046	1.158	1.161	0.879	0.869	39.7	54.3
106.0	4.308	7.462	2.046	1.158	1.162	0.880	0.870	39.7	54.5
108.0	4.309	7.466	2.045	1.158	1.163	0.881	0.871	39.8	54.6
110.0	4.310	7.469	2.045	1.160	1.163	0.882	0.872	39.9	54.8
112.0	4.311	7.473	2.045	1.161	1.164	0.883	0.873	39.9	54.9
114.0	4.312	7.477	2.045	1.163	1.165	0.883	0.873	39.9	55.0
116.0	4.314	7.482	2.045	1.166	1.165	0.884	0.874	40.0	55.1
118.0	4.315	7.486	2.046	1.168	1.165	0.884	0.874	40.0	55.1
120.0	4.316	7.490	2.046	1.170	1.166	0.884	0.875	40.0	55.2
122.0	4.317	7.494	2.046	1.171	1.166	0.884	0.875	40.0	55.2
124.0	4.318	7.498	2.046	1.172	1.166	0.884	0.875	40.0	55.2
126.0	4.319	7.501	2.047	1.173	1.166	0.884	0.875	40.0	55.2
128.0	4.319	7.505	2.047	1.174	1.165	0.884	0.875	40.0	55.1
130.0	4.320	7.508	2.047	1.175	1.165	0.884	0.875	40.0	55.1
132.0	4.320	7.510	2.047	1.175	1.165	0.884	0.874	40.0	55.1
134.0	4.321	7.513	2.048	1.175	1.165	0.884	0.874	40.0	55.1
136.0	4.321	7.515	2.048	1.175	1.164	0.883	0.874	40.0	55.1
138.0	4.321	7.517	2.048	1.176	1.164	0.883	0.873	40.0	55.1
140.0	4.321	7.518	2.049	1.176	1.163	0.883	0.873	40.0	55.0
142.0	4.321	7.519	2.049	1.176	1.163	0.882	0.873	40.0	55.0
144.0	4.321	7.519	2.049	1.177	1.162	0.882	0.872	40.0	55.0
146.0	4.321	7.520	2.050	1.177	1.162	0.882	0.872	40.1	55.1
148.0	4.321	7.520	2.050	1.178	1.162	0.881	0.872	40.1	55.1
150.0	4.321	7.519	2.051	1.178	1.161	0.881	0.871	40.1	55.1
152.0	4.321	7.519	2.051	1.179	1.161	0.881	0.871	40.1	55.1
154.0	4.320	7.518	2.051	1.180	1.161	0.880	0.871	40.1	55.1
156.0	4.320	7.517	2.052	1.181	1.161	0.880	0.871	40.1	55.1
158.0	4.320	7.516	2.052	1.181	1.160	0.880	0.871	40.0	55.1
160.0	4.319	7.515	2.052	1.182	1.160	0.880	0.870	40.0	55.1
162.0	4.319	7.514	2.052	1.182	1.160	0.880	0.870	40.0	55.1
164.0	4.319	7.512	2.052	1.183	1.160	0.880	0.870	40.0	55.1
166.0	4.318	7.511	2.052	1.183	1.160	0.880	0.870	40.0	55.1
168.0	4.318	7.510	2.053	1.183	1.160	0.880	0.870	40.0	55.1
170.0	4.318	7.509	2.052	1.184	1.160	0.880	0.870	40.0	55.0
172.0	4.318	7.508	2.052	1.183	1.160	0.880	0.870	40.0	55.0
174.0	4.317	7.507	2.052	1.183	1.160	0.880	0.870	40.0	55.0
176.0	4.317	7.506	2.052	1.183	1.160	0.880	0.870	40.0	55.0
178.0	4.317	7.505	2.052	1.183	1.161	0.880	0.870	40.0	55.0
180.0	4.317	7.504	2.052	1.182	1.161	0.880	0.870	40.0	55.0

CALCULATED FINAL CONDITIONS

F= 2.932, B1= 2.052, B2= 1.182, CF= 0.03021, C1= 0.04317
C2= 0.07504, TF= 90.8, TS1= 211.0, T1= 190.2, S1= 1.161

EXPERIMENT 5

CLOSED LOOP RESPONSE TO A STEP UP IN FEED RATE

INPUT DATA

INITIAL CONDITIONS
F= 2.930, B1= 2.050, B2= 1.225, CF= 0.03190, C1= 0.04560
C2= 0.07620, TF= 90.5, TS1= 207.5, T1= 189.0, T2= 150.0
HSI= 1175.1

FINAL CONDITIONS
F= 3.400, B1= 2.350, B2= 1.330, CF= 0.03000, C1= 0.04300
C2= 0.07620, TF= 90.5, TS1= 213.5, T1= 194.0, T2= 150.0
HSI= 1175.1

CALCULATED PARAMETERS
UA1= 65.92, UA2= 22.13, HL2= 19.39, HL3= 77.54

CONTROLLER SETTINGS
KL1= 80.0, KL2= 175.0, KC2= 130.0, TL1= 6.0, TL2= 6.0
TC2= 7.0, TDC2= 5.0

CALCULATED INITIAL CONDITIONS
F= 2.929, B1= 2.057, B2= 1.226, CF= 0.03190, C1= 0.04541
C2= 0.07622, TF= 90.5, TS1= 205.2, T1= 187.9, SI= 1.141

EXPERIMENT 5

CLOSED LOOP RESPONSE TO A STEP UP IN FEED RATE

INPUT DATA

INITIAL CONDITIONS
F= 2.930, B1= 2.050, B2= 1.225, CF= 0.03190, C1= 0.04560
C2= 0.07620, TF= 90.5, TS1= 207.5, T1= 189.0, T2= 150.0
HS1= 1175.1

FINAL CONDITIONS
F= 3.400, B1= 2.350, B2= 1.330, CF= 0.03000, C1= 0.04300
C2= 0.07620, TF= 90.5, TS1= 213.5, T1= 194.0, T2= 150.0
HS1= 1175.1

CALCULATED PARAMETERS
UA1= 65.92, UA2= 22.13, HL2= 19.39, HL3= 77.54

CONTROLLER SETTINGS
KL1= 80.0, KL2= 175.0, KC2= 130.0, TL1= 6.0, TL2= 6.0
TC2= 7.0, TDC2= 5.0

CALCULATED INITIAL CONDITIONS
F= 2.929, B1= 2.057, B2= 1.226, CF= 0.03190, C1= 0.04541
C2= 0.07622, TF= 90.5, TS1= 205.2, T1= 187.9, S1= 1.141

TIME	C1	C2	B1	B2	SI	O1	O2	L1	L2
-2.0	4.541	7.622	2.057	1.226	1.141	0.872	0.832	40.0	55.0
-0.0	4.541	7.622	2.057	1.226	1.141	0.872	0.832	40.0	55.0
2.0	4.510	7.607	2.147	1.239	1.152	0.849	0.813	44.0	55.5
4.0	4.466	7.565	2.248	1.283	1.165	0.850	0.815	47.5	56.8
6.0	4.410	7.504	2.343	1.351	1.180	0.859	0.828	49.9	58.4
8.0	4.364	7.431	2.427	1.438	1.197	0.872	0.844	51.3	60.0
10.0	4.326	7.350	2.498	1.536	1.216	0.886	0.862	51.8	61.3
12.0	4.296	7.268	2.555	1.634	1.235	0.902	0.881	51.4	62.0
14.0	4.272	7.189	2.596	1.719	1.255	0.918	0.900	50.4	62.1
16.0	4.255	7.118	2.622	1.783	1.275	0.935	0.919	48.8	61.6
18.0	4.243	7.057	2.634	1.820	1.296	0.952	0.937	46.9	60.5
20.0	4.236	7.008	2.631	1.827	1.315	0.969	0.955	44.8	59.1
22.0	4.233	6.972	2.616	1.807	1.334	0.986	0.972	42.6	57.5
24.0	4.233	6.952	2.591	1.765	1.352	1.002	0.988	40.5	55.8
26.0	4.237	6.946	2.556	1.707	1.368	1.016	1.002	38.5	54.2
28.0	4.244	6.956	2.515	1.637	1.383	1.029	1.014	36.7	52.7
30.0	4.252	6.979	2.470	1.562	1.396	1.041	1.025	35.3	51.4
32.0	4.262	7.016	2.423	1.484	1.407	1.051	1.033	34.2	50.3
34.0	4.273	7.065	2.376	1.407	1.415	1.060	1.040	33.5	49.5
36.0	4.284	7.124	2.332	1.334	1.422	1.067	1.046	33.2	48.9
38.0	4.295	7.190	2.293	1.267	1.427	1.072	1.049	33.2	48.5
40.0	4.306	7.262	2.261	1.208	1.430	1.075	1.052	33.6	48.4
42.0	4.316	7.336	2.236	1.158	1.432	1.077	1.053	34.3	48.5
44.0	4.325	7.410	2.219	1.117	1.432	1.078	1.053	35.1	48.9
46.0	4.333	7.482	2.210	1.087	1.430	1.078	1.052	36.1	49.5
48.0	4.340	7.549	2.208	1.067	1.428	1.077	1.051	37.1	50.3
50.0	4.346	7.610	2.213	1.059	1.425	1.075	1.049	38.2	51.3
52.0	4.351	7.663	2.223	1.061	1.422	1.072	1.047	39.2	52.5
54.0	4.354	7.708	2.237	1.074	1.418	1.069	1.044	40.1	53.7
56.0	4.356	7.744	2.254	1.096	1.413	1.066	1.042	40.8	54.9
58.0	4.357	7.772	2.272	1.126	1.409	1.062	1.039	41.5	56.1
60.0	4.358	7.791	2.291	1.163	1.405	1.058	1.036	41.9	57.1
62.0	4.357	7.802	2.309	1.204	1.400	1.055	1.033	42.2	57.9
64.0	4.356	7.807	2.325	1.247	1.396	1.051	1.030	42.4	58.5
66.0	4.354	7.805	2.341	1.290	1.393	1.048	1.027	42.5	58.9
68.0	4.352	7.799	2.354	1.329	1.389	1.045	1.025	42.4	59.0
70.0	4.349	7.789	2.364	1.363	1.386	1.042	1.022	42.2	58.9
72.0	4.346	7.775	2.372	1.390	1.384	1.040	1.020	42.0	58.6
74.0	4.343	7.760	2.378	1.410	1.382	1.038	1.018	41.7	58.2
76.0	4.340	7.744	2.382	1.422	1.380	1.036	1.017	41.4	57.6
78.0	4.337	7.727	2.384	1.427	1.378	1.035	1.015	41.1	57.0
80.0	4.334	7.710	2.384	1.427	1.377	1.034	1.014	40.8	56.4
82.0	4.331	7.693	2.383	1.421	1.376	1.033	1.013	40.5	55.9
84.0	4.328	7.678	2.380	1.413	1.376	1.032	1.012	40.2	55.4
86.0	4.326	7.664	2.377	1.402	1.375	1.032	1.011	40.0	54.9
88.0	4.324	7.652	2.373	1.390	1.375	1.031	1.011	39.8	54.6
90.0	4.322	7.641	2.369	1.378	1.375	1.031	1.011	39.7	54.4
92.0	4.320	7.631	2.365	1.366	1.375	1.031	1.011	39.5	54.2
94.0	4.318	7.624	2.361	1.356	1.376	1.032	1.011	39.5	54.1
96.0	4.317	7.617	2.357	1.346	1.376	1.032	1.011	39.5	54.1
98.0	4.316	7.612	2.354	1.339	1.376	1.032	1.011	39.5	54.1

TIME	C1	C2	B1	B2	S1	O1	O2	L1	L2
-2.0	4.541	7.622	2.057	1.226	1.141	0.872	0.832	40.0	55.0
-0.0	4.541	7.622	2.057	1.226	1.141	0.872	0.832	40.0	55.0
2.0	4.510	7.607	2.147	1.239	1.152	0.849	0.813	44.0	55.5
4.0	4.466	7.565	2.248	1.283	1.165	0.850	0.815	47.5	56.8
6.0	4.410	7.504	2.343	1.351	1.180	0.859	0.828	49.9	58.4
8.0	4.364	7.431	2.427	1.438	1.197	0.872	0.844	51.3	60.0
10.0	4.326	7.350	2.498	1.536	1.216	0.886	0.862	51.8	61.3
12.0	4.296	7.268	2.555	1.634	1.235	0.902	0.881	51.4	62.0
14.0	4.272	7.189	2.596	1.719	1.255	0.918	0.900	50.4	62.1
16.0	4.255	7.118	2.622	1.783	1.275	0.935	0.919	48.8	61.6
18.0	4.243	7.057	2.634	1.820	1.296	0.952	0.937	46.9	60.5
20.0	4.236	7.008	2.631	1.827	1.315	0.969	0.955	44.8	59.1
22.0	4.233	6.972	2.616	1.807	1.334	0.986	0.972	42.6	57.5
24.0	4.233	6.952	2.591	1.765	1.352	1.002	0.988	40.5	55.8
26.0	4.237	6.946	2.556	1.707	1.368	1.016	1.002	38.5	54.2
28.0	4.244	6.956	2.515	1.637	1.383	1.029	1.014	36.7	52.7
30.0	4.252	6.979	2.470	1.562	1.396	1.041	1.025	35.3	51.4
32.0	4.262	7.016	2.423	1.484	1.407	1.051	1.033	34.2	50.3
34.0	4.273	7.065	2.376	1.407	1.415	1.060	1.040	33.5	49.5
36.0	4.284	7.124	2.332	1.334	1.422	1.067	1.046	33.2	48.9
38.0	4.295	7.190	2.293	1.267	1.427	1.072	1.049	33.2	48.5
40.0	4.306	7.262	2.261	1.208	1.430	1.075	1.052	33.6	48.4
42.0	4.316	7.336	2.236	1.158	1.432	1.077	1.053	34.3	48.5
44.0	4.325	7.410	2.219	1.117	1.432	1.078	1.053	35.1	48.9
46.0	4.333	7.482	2.210	1.087	1.430	1.078	1.052	36.1	49.5
48.0	4.340	7.549	2.208	1.067	1.428	1.077	1.051	37.1	50.3
50.0	4.346	7.610	2.213	1.059	1.425	1.075	1.049	38.2	51.3
52.0	4.351	7.663	2.223	1.061	1.422	1.072	1.047	39.2	52.5
54.0	4.354	7.708	2.237	1.074	1.418	1.069	1.044	40.1	53.7
56.0	4.356	7.744	2.254	1.096	1.413	1.066	1.042	40.8	54.9
58.0	4.357	7.772	2.272	1.126	1.409	1.062	1.039	41.5	56.1
60.0	4.358	7.791	2.291	1.163	1.405	1.058	1.036	41.9	57.1
62.0	4.357	7.802	2.309	1.204	1.400	1.055	1.033	42.2	57.9
64.0	4.356	7.807	2.325	1.247	1.396	1.051	1.030	42.4	58.5
66.0	4.354	7.805	2.341	1.290	1.393	1.048	1.027	42.5	58.9
68.0	4.352	7.799	2.354	1.329	1.389	1.045	1.025	42.4	59.0
70.0	4.349	7.789	2.364	1.363	1.386	1.042	1.022	42.2	58.9
72.0	4.346	7.775	2.372	1.390	1.384	1.040	1.020	42.0	58.6
74.0	4.343	7.760	2.378	1.410	1.382	1.038	1.018	41.7	58.2
76.0	4.340	7.744	2.382	1.422	1.380	1.036	1.017	41.4	57.6
78.0	4.337	7.727	2.384	1.427	1.378	1.035	1.015	41.1	57.0
80.0	4.334	7.710	2.384	1.427	1.377	1.034	1.014	40.8	56.4
82.0	4.331	7.693	2.383	1.421	1.376	1.033	1.013	40.5	55.9
84.0	4.328	7.678	2.380	1.413	1.376	1.032	1.012	40.2	55.4
86.0	4.326	7.664	2.377	1.402	1.375	1.032	1.011	40.0	54.9
88.0	4.324	7.652	2.373	1.390	1.375	1.031	1.011	39.8	54.6
90.0	4.322	7.641	2.369	1.378	1.375	1.031	1.011	39.7	54.4
92.0	4.320	7.631	2.365	1.366	1.375	1.031	1.011	39.5	54.2
94.0	4.318	7.624	2.361	1.356	1.376	1.032	1.011	39.5	54.1
96.0	4.317	7.617	2.357	1.346	1.376	1.032	1.011	39.5	54.1
98.0	4.316	7.612	2.354	1.339	1.376	1.032	1.011	39.5	54.1

.CONTD

TIME	C1	C2	B1	B2	SI	O1	O2	L1	L2
100.0	4.315	7.608	2.351	1.332	1.377	1.033	1.011	39.5	54.2
102.0	4.314	7.605	2.349	1.328	1.377	1.033	1.012	39.5	54.3
104.0	4.314	7.602	2.348	1.324	1.378	1.033	1.012	39.6	54.4
106.0	4.313	7.601	2.347	1.322	1.379	1.034	1.012	39.7	54.5
108.0	4.313	7.600	2.346	1.322	1.379	1.034	1.013	39.7	54.6
110.0	4.313	7.599	2.346	1.322	1.380	1.035	1.014	39.8	54.7
112.0	4.313	7.598	2.346	1.322	1.381	1.035	1.014	39.9	54.8
114.0	4.313	7.598	2.346	1.324	1.381	1.036	1.015	39.9	54.9
116.0	4.313	7.599	2.347	1.325	1.382	1.037	1.015	40.0	55.0
118.0	4.314	7.599	2.347	1.327	1.382	1.037	1.016	40.0	55.0
120.0	4.314	7.600	2.348	1.329	1.383	1.038	1.016	40.0	55.1
122.0	4.315	7.600	2.348	1.330	1.384	1.038	1.017	40.0	55.1
124.0	4.315	7.601	2.349	1.332	1.384	1.038	1.017	40.0	55.1
126.0	4.316	7.602	2.349	1.332	1.384	1.039	1.018	40.0	55.1
128.0	4.316	7.603	2.349	1.333	1.385	1.039	1.018	40.0	55.1
130.0	4.317	7.605	2.349	1.333	1.385	1.039	1.018	40.0	55.1
132.0	4.317	7.606	2.349	1.333	1.385	1.040	1.019	40.0	55.0
134.0	4.318	7.608	2.349	1.333	1.386	1.040	1.019	40.0	55.0
136.0	4.318	7.610	2.349	1.332	1.386	1.040	1.019	40.0	55.0
138.0	4.319	7.612	2.348	1.331	1.386	1.040	1.019	40.0	55.0
140.0	4.319	7.613	2.348	1.330	1.386	1.040	1.019	40.0	55.0
142.0	4.320	7.615	2.348	1.329	1.386	1.040	1.019	40.0	54.9
144.0	4.320	7.617	2.347	1.329	1.386	1.040	1.019	40.0	54.9
146.0	4.321	7.619	2.347	1.328	1.386	1.040	1.019	40.0	54.9
148.0	4.321	7.621	2.347	1.327	1.386	1.040	1.019	40.0	54.9
150.0	4.321	7.623	2.347	1.327	1.386	1.040	1.019	40.0	54.9
152.0	4.321	7.624	2.346	1.326	1.386	1.040	1.019	40.0	54.9
154.0	4.321	7.625	2.346	1.326	1.386	1.040	1.019	40.0	55.0
156.0	4.322	7.627	2.347	1.326	1.385	1.040	1.019	40.0	55.0
158.0	4.322	7.628	2.347	1.326	1.385	1.040	1.019	40.0	55.0
160.0	4.322	7.628	2.347	1.327	1.385	1.040	1.019	40.0	55.0
162.0	4.322	7.629	2.347	1.327	1.385	1.040	1.018	40.0	55.0
164.0	4.322	7.629	2.347	1.328	1.385	1.039	1.018	40.0	55.0
166.0	4.321	7.630	2.348	1.328	1.384	1.039	1.018	40.0	55.0
168.0	4.321	7.630	2.348	1.329	1.384	1.039	1.018	40.0	55.1
170.0	4.321	7.629	2.348	1.330	1.384	1.039	1.018	40.0	55.1
172.0	4.321	7.629	2.349	1.331	1.384	1.039	1.018	40.0	55.1
174.0	4.321	7.629	2.349	1.331	1.384	1.039	1.018	40.0	55.1
176.0	4.321	7.628	2.349	1.332	1.384	1.039	1.018	40.0	55.1
178.0	4.321	7.628	2.349	1.332	1.384	1.039	1.017	40.0	55.1
180.0	4.321	7.627	2.349	1.333	1.384	1.038	1.017	40.0	55.1

CALCULATED FINAL CONDITIONS
F= 3.388, B1= 2.349, B2= 1.333, CF= 0.02995, C1= 0.04321
C2= 0.07627, TF= 90.5, TS1= 215.9, T1= 195.2, SI= 1.384

..CONTD

TIME	C1	C2	B1	B2	S1	O1	O2	L1	L2
100.0	4.315	7.608	2.351	1.332	1.377	1.033	1.011	39.5	54.2
102.0	4.314	7.605	2.349	1.328	1.377	1.033	1.012	39.5	54.3
104.0	4.314	7.602	2.348	1.324	1.378	1.033	1.012	39.6	54.4
106.0	4.313	7.601	2.347	1.322	1.379	1.034	1.012	39.7	54.5
108.0	4.313	7.600	2.346	1.322	1.379	1.034	1.013	39.7	54.6
110.0	4.313	7.599	2.346	1.322	1.380	1.035	1.014	39.8	54.7
112.0	4.313	7.598	2.346	1.322	1.381	1.035	1.014	39.9	54.8
114.0	4.313	7.598	2.346	1.324	1.381	1.036	1.015	39.9	54.9
116.0	4.313	7.599	2.347	1.325	1.382	1.037	1.015	40.0	55.0
118.0	4.314	7.599	2.347	1.327	1.382	1.037	1.016	40.0	55.0
120.0	4.314	7.600	2.348	1.329	1.383	1.038	1.016	40.0	55.1
122.0	4.315	7.600	2.348	1.330	1.384	1.038	1.017	40.0	55.1
124.0	4.315	7.601	2.349	1.332	1.384	1.038	1.017	40.0	55.1
126.0	4.316	7.602	2.349	1.332	1.384	1.039	1.018	40.0	55.1
128.0	4.316	7.603	2.349	1.333	1.385	1.039	1.018	40.0	55.1
130.0	4.317	7.605	2.349	1.333	1.385	1.039	1.018	40.0	55.1
132.0	4.317	7.606	2.349	1.333	1.385	1.040	1.019	40.0	55.0
134.0	4.318	7.608	2.349	1.333	1.386	1.040	1.019	40.0	55.0
136.0	4.318	7.610	2.349	1.332	1.386	1.040	1.019	40.0	55.0
138.0	4.319	7.612	2.348	1.331	1.386	1.040	1.019	40.0	55.0
140.0	4.319	7.613	2.348	1.330	1.386	1.040	1.019	40.0	55.0
142.0	4.320	7.615	2.348	1.329	1.386	1.040	1.019	40.0	54.9
144.0	4.320	7.617	2.347	1.329	1.386	1.040	1.019	40.0	54.9
146.0	4.321	7.619	2.347	1.328	1.386	1.040	1.019	40.0	54.9
148.0	4.321	7.621	2.347	1.327	1.386	1.040	1.019	40.0	54.9
150.0	4.321	7.623	2.347	1.327	1.386	1.040	1.019	40.0	54.9
152.0	4.321	7.624	2.346	1.326	1.386	1.040	1.019	40.0	54.9
154.0	4.321	7.625	2.346	1.326	1.386	1.040	1.019	40.0	55.0
156.0	4.322	7.627	2.347	1.326	1.385	1.040	1.019	40.0	55.0
158.0	4.322	7.628	2.347	1.326	1.385	1.040	1.019	40.0	55.0
160.0	4.322	7.628	2.347	1.327	1.385	1.040	1.019	40.0	55.0
162.0	4.322	7.629	2.347	1.327	1.385	1.040	1.018	40.0	55.0
164.0	4.322	7.629	2.347	1.328	1.385	1.039	1.018	40.0	55.0
166.0	4.321	7.630	2.348	1.328	1.384	1.039	1.018	40.0	55.0
168.0	4.321	7.630	2.348	1.329	1.384	1.039	1.018	40.0	55.1
170.0	4.321	7.629	2.348	1.330	1.384	1.039	1.018	40.0	55.1
172.0	4.321	7.629	2.349	1.331	1.384	1.039	1.018	40.0	55.1
174.0	4.321	7.629	2.349	1.331	1.384	1.039	1.018	40.0	55.1
176.0	4.321	7.628	2.349	1.332	1.384	1.039	1.018	40.0	55.1
178.0	4.321	7.628	2.349	1.332	1.384	1.039	1.017	40.0	55.1
180.0	4.321	7.627	2.349	1.333	1.384	1.038	1.017	40.0	55.1

CALCULATED FINAL CONDITIONS

F= 3.388, B1= 2.349, B2= 1.333, CF= 0.02995, C1= 0.04321

C2= 0.07627, TF= 90.5, TS1= 215.9, T1= 195.2, S1= 1.384

EXPERIMENT 6

CLOSED LOOP RESPONSE TO A STEP CHANGE IN CONC SET PT

INPUT DATA

INITIAL CONDITIONS
F= 3.400, B1= 2.410, B2= 1.420, CF= 0.03160, C1= 0.04460
C2= 0.07570, TF= 87.5, TS1= 214.0, T1= 182.5, T2= 150.0
HSI= 1173.8

FINAL CONDITIONS
F= 3.400, B1= 2.240, B2= 1.125, CF= 0.02900, C1= 0.04380
C2= 0.08740, TF= 87.5, TS1= 218.5, T1= 187.0, T2= 150.0
HSI= 1173.8

CALCULATED PARAMETERS
UA1= 43.88, UA2= 29.96, HL2= 14.47, HL3= 57.86

CONTROLLER SETTINGS
KL1= 80.0, KL2= 160.0, KC2= 120.0, TL1= 6.0, TL2= 6.0
TC2= 7.0, TDC2= 5.0

CALCULATED INITIAL CONDITIONS
F= 3.397, B1= 2.400, B2= 1.418, CF= 0.03160, C1= 0.04473
C2= 0.07570, TF= 87.5, TS1= 212.1, T1= 182.4, SI= 1.315

EXPERIMENT 6

CLOSED LOOP RESPONSE TO A STEP CHANGE IN CONC SET PT

INPUT DATA

INITIAL CONDITIONS
F= 3.400, B1= 2.410, B2= 1.420, CF= 0.03160, C1= 0.04460
C2= 0.07570, TF= 87.5, TS1= 214.0, T1= 182.5, T2= 150.0
HSI= 1173.8

FINAL CONDITIONS
F= 3.400, B1= 2.240, B2= 1.125, CF= 0.02900, C1= 0.04380
C2= 0.08740, TF= 87.5, TS1= 218.5, T1= 187.0, T2= 150.0
HSI= 1173.8

CALCULATED PARAMETERS
UA1= 43.88, UA2= 29.96, HL2= 14.47, HL3= 57.86

CONTROLLER SETTINGS
KL1= 80.0, KL2= 160.0, KC2= 120.0, TL1= 6.0, TL2= 6.0
TC2= 7.0, TDC2= 5.0

CALCULATED INITIAL CONDITIONS
F= 3.397, B1= 2.400, B2= 1.418, CF= 0.03160, C1= 0.04473
C2= 0.07570, TF= 87.5, TS1= 212.1, T1= 182.4, S1= 1.315

TIME	C1	C2	B1	B2	SI	O1	O2	L1	L2
-2.0	4.473	7.570	2.400	1.418	1.315	0.997	0.982	40.0	55.0
-0.0	4.473	7.570	2.400	1.418	1.315	0.997	0.982	40.0	55.0
2.0	4.485	7.597	2.391	1.401	1.450	1.087	1.069	39.5	54.5
4.0	4.489	7.658	2.370	1.362	1.469	1.118	1.104	38.6	53.6
6.0	4.472	7.735	2.344	1.314	1.488	1.136	1.122	37.7	52.6
8.0	4.460	7.819	2.314	1.260	1.504	1.151	1.137	36.9	51.7
10.0	4.453	7.908	2.283	1.204	1.518	1.164	1.149	36.3	50.9
12.0	4.449	8.004	2.253	1.148	1.528	1.174	1.159	35.9	50.3
14.0	4.448	8.104	2.223	1.094	1.536	1.182	1.166	35.7	49.8
16.0	4.448	8.207	2.197	1.044	1.541	1.188	1.170	35.7	49.6
18.0	4.449	8.312	2.175	1.000	1.544	1.191	1.173	35.9	49.5
20.0	4.451	8.416	2.158	0.962	1.545	1.193	1.174	36.3	49.6
22.0	4.453	8.516	2.147	0.932	1.544	1.193	1.174	36.9	49.9
24.0	4.454	8.612	2.141	0.909	1.541	1.191	1.172	37.5	50.4
26.0	4.455	8.699	2.140	0.894	1.537	1.188	1.170	38.2	51.1
28.0	4.454	8.778	2.144	0.888	1.533	1.185	1.166	38.9	52.0
30.0	4.453	8.846	2.152	0.891	1.527	1.180	1.162	39.6	53.0
32.0	4.452	8.903	2.164	0.902	1.521	1.176	1.157	40.2	54.0
34.0	4.449	8.948	2.177	0.921	1.515	1.170	1.153	40.7	55.1
36.0	4.445	8.981	2.192	0.947	1.508	1.165	1.148	41.2	56.1
38.0	4.441	9.003	2.207	0.979	1.502	1.160	1.143	41.6	57.0
40.0	4.435	9.015	2.222	1.016	1.496	1.155	1.138	41.8	57.8
42.0	4.430	9.017	2.237	1.054	1.491	1.150	1.134	42.0	58.4
44.0	4.424	9.011	2.250	1.094	1.486	1.145	1.130	42.0	58.8
46.0	4.418	8.998	2.262	1.131	1.481	1.141	1.126	42.0	59.0
48.0	4.411	8.980	2.272	1.164	1.478	1.138	1.123	41.9	58.9
50.0	4.405	8.957	2.280	1.192	1.475	1.135	1.120	41.8	58.7
52.0	4.398	8.931	2.286	1.213	1.472	1.132	1.118	41.6	58.3
54.0	4.392	8.903	2.291	1.228	1.470	1.131	1.116	41.3	57.8
56.0	4.387	8.875	2.293	1.235	1.469	1.129	1.114	41.1	57.2
58.0	4.381	8.846	2.294	1.237	1.468	1.128	1.114	40.8	56.7
60.0	4.377	8.819	2.293	1.234	1.468	1.128	1.113	40.5	56.1
62.0	4.372	8.793	2.292	1.227	1.468	1.128	1.113	40.3	55.6
64.0	4.368	8.769	2.289	1.217	1.469	1.128	1.113	40.1	55.1
66.0	4.365	8.748	2.285	1.206	1.470	1.129	1.114	39.9	54.7
68.0	4.362	8.729	2.281	1.193	1.471	1.130	1.115	39.7	54.4
70.0	4.360	8.714	2.277	1.180	1.472	1.131	1.115	39.6	54.2
72.0	4.358	8.701	2.272	1.168	1.474	1.132	1.117	39.5	54.0
74.0	4.357	8.691	2.268	1.156	1.475	1.133	1.118	39.4	53.9
76.0	4.356	8.684	2.264	1.146	1.477	1.135	1.119	39.4	53.9
78.0	4.356	8.679	2.260	1.137	1.478	1.136	1.120	39.4	53.9
80.0	4.356	8.676	2.257	1.129	1.480	1.137	1.121	39.4	54.0
82.0	4.356	8.675	2.254	1.123	1.481	1.138	1.122	39.5	54.0
84.0	4.356	8.676	2.252	1.118	1.483	1.140	1.124	39.5	54.1
86.0	4.357	8.678	2.250	1.114	1.484	1.141	1.125	39.6	54.3
88.0	4.358	8.681	2.249	1.111	1.485	1.142	1.126	39.6	54.4
90.0	4.359	8.685	2.248	1.110	1.486	1.143	1.127	39.7	54.5
92.0	4.360	8.689	2.247	1.109	1.487	1.143	1.127	39.7	54.6
94.0	4.361	8.694	2.247	1.109	1.488	1.144	1.128	39.8	54.7
96.0	4.362	8.699	2.247	1.110	1.488	1.145	1.129	39.9	54.8
98.0	4.363	8.705	2.247	1.111	1.489	1.145	1.129	39.9	54.9

..CONTD

TIME	C1	C2	B1	B2	SI	O1	O2	L1	L2
100.0	4.364	8.710	2.248	1.112	1.489	1.146	1.130	39.9	55.0
102.0	4.365	8.715	2.248	1.113	1.490	1.146	1.130	40.0	55.0
104.0	4.366	8.720	2.248	1.115	1.490	1.146	1.130	40.0	55.1
106.0	4.367	8.724	2.249	1.116	1.490	1.146	1.130	40.0	55.1
108.0	4.368	8.729	2.249	1.118	1.490	1.146	1.131	40.0	55.1
110.0	4.368	8.733	2.250	1.119	1.490	1.146	1.131	40.0	55.1
112.0	4.369	8.737	2.250	1.120	1.490	1.146	1.130	40.1	55.1
114.0	4.369	8.740	2.251	1.121	1.490	1.146	1.130	40.1	55.1
116.0	4.370	8.743	2.251	1.122	1.489	1.146	1.130	40.1	55.1
118.0	4.370	8.745	2.251	1.122	1.489	1.146	1.130	40.1	55.1
120.0	4.371	8.748	2.251	1.123	1.489	1.146	1.130	40.1	55.1
122.0	4.371	8.750	2.252	1.123	1.489	1.145	1.130	40.0	55.1
124.0	4.371	8.751	2.252	1.124	1.488	1.145	1.129	40.0	55.1
126.0	4.371	8.752	2.252	1.124	1.488	1.145	1.129	40.0	55.1
128.0	4.371	8.753	2.252	1.124	1.488	1.145	1.129	40.0	55.1
130.0	4.371	8.754	2.253	1.125	1.487	1.144	1.128	40.0	55.0
132.0	4.371	8.754	2.253	1.125	1.487	1.144	1.128	40.0	55.0
134.0	4.370	8.754	2.253	1.125	1.487	1.144	1.128	40.0	55.0
136.0	4.370	8.754	2.253	1.126	1.486	1.144	1.128	40.0	55.0
138.0	4.370	8.753	2.254	1.126	1.486	1.143	1.127	40.0	55.0
140.0	4.370	8.752	2.254	1.126	1.486	1.143	1.127	40.0	55.0
142.0	4.369	8.751	2.254	1.127	1.486	1.143	1.127	40.0	55.0
144.0	4.369	8.750	2.254	1.127	1.486	1.143	1.127	40.0	55.0
146.0	4.369	8.749	2.254	1.128	1.485	1.143	1.127	40.0	55.0
148.0	4.369	8.748	2.255	1.128	1.485	1.143	1.127	40.0	55.0
150.0	4.368	8.747	2.255	1.128	1.485	1.143	1.127	40.0	55.0
152.0	4.368	8.746	2.255	1.129	1.485	1.143	1.127	40.0	55.0
154.0	4.368	8.744	2.255	1.129	1.485	1.142	1.127	40.0	55.0
156.0	4.368	8.743	2.255	1.129	1.485	1.142	1.127	40.0	55.0
158.0	4.368	8.742	2.255	1.129	1.485	1.143	1.127	40.0	55.0
160.0	4.367	8.741	2.255	1.129	1.485	1.143	1.127	40.0	55.0
162.0	4.367	8.740	2.255	1.129	1.485	1.143	1.127	40.0	55.0
164.0	4.367	8.739	2.255	1.129	1.485	1.143	1.127	40.0	55.0
166.0	4.367	8.739	2.255	1.128	1.486	1.143	1.127	40.0	55.0
168.0	4.367	8.738	2.254	1.128	1.486	1.143	1.127	40.0	55.0
170.0	4.367	8.738	2.254	1.128	1.486	1.143	1.127	40.0	55.0
172.0	4.367	8.737	2.254	1.128	1.486	1.143	1.127	40.0	55.0
174.0	4.367	8.737	2.254	1.127	1.486	1.143	1.127	40.0	55.0
176.0	4.367	8.737	2.254	1.127	1.486	1.143	1.127	40.0	55.0
178.0	4.367	8.737	2.254	1.127	1.486	1.143	1.127	40.0	55.0
180.0	4.367	8.737	2.254	1.126	1.486	1.143	1.127	40.0	55.0

CALCULATED FINAL CONDITIONS
F= 3.397, B1= 2.254, B2= 1.126, CF= 0.02898, C1= 0.04367
C2= 0.08737, TF= 87.5, TS1= 220.4, T1= 187.1, SI= 1.486

..CONTD

TIME	C1	C2	B1	B2	S1	O1	O2	L1	L2
100.0	4.364	8.710	2.248	1.112	1.489	1.146	1.130	39.9	55.0
102.0	4.365	8.715	2.248	1.113	1.490	1.146	1.130	40.0	55.0
104.0	4.366	8.720	2.248	1.115	1.490	1.146	1.130	40.0	55.1
106.0	4.367	8.724	2.249	1.116	1.490	1.146	1.130	40.0	55.1
108.0	4.368	8.729	2.249	1.118	1.490	1.146	1.131	40.0	55.1
110.0	4.368	8.733	2.250	1.119	1.490	1.146	1.131	40.0	55.1
112.0	4.369	8.737	2.250	1.120	1.490	1.146	1.130	40.1	55.1
114.0	4.369	8.740	2.251	1.121	1.490	1.146	1.130	40.1	55.1
116.0	4.370	8.743	2.251	1.122	1.489	1.146	1.130	40.1	55.1
118.0	4.370	8.745	2.251	1.122	1.489	1.146	1.130	40.1	55.1
120.0	4.371	8.748	2.251	1.123	1.489	1.146	1.130	40.1	55.1
122.0	4.371	8.750	2.252	1.123	1.489	1.145	1.130	40.0	55.1
124.0	4.371	8.751	2.252	1.124	1.488	1.145	1.129	40.0	55.1
126.0	4.371	8.752	2.252	1.124	1.488	1.145	1.129	40.0	55.1
128.0	4.371	8.753	2.252	1.124	1.488	1.145	1.129	40.0	55.1
130.0	4.371	8.754	2.253	1.125	1.487	1.144	1.128	40.0	55.0
132.0	4.371	8.754	2.253	1.125	1.487	1.144	1.128	40.0	55.0
134.0	4.370	8.754	2.253	1.125	1.487	1.144	1.128	40.0	55.0
136.0	4.370	8.754	2.253	1.126	1.486	1.144	1.128	40.0	55.0
138.0	4.370	8.753	2.254	1.126	1.486	1.143	1.127	40.0	55.0
140.0	4.370	8.752	2.254	1.126	1.486	1.143	1.127	40.0	55.0
142.0	4.369	8.751	2.254	1.127	1.486	1.143	1.127	40.0	55.0
144.0	4.369	8.750	2.254	1.127	1.486	1.143	1.127	40.0	55.0
146.0	4.369	8.749	2.254	1.128	1.485	1.143	1.127	40.0	55.0
148.0	4.369	8.748	2.255	1.128	1.485	1.143	1.127	40.0	55.0
150.0	4.368	8.747	2.255	1.128	1.485	1.143	1.127	40.0	55.0
152.0	4.368	8.746	2.255	1.129	1.485	1.143	1.127	40.0	55.0
154.0	4.368	8.744	2.255	1.129	1.485	1.142	1.127	40.0	55.0
156.0	4.368	8.743	2.255	1.129	1.485	1.142	1.127	40.0	55.0
158.0	4.368	8.742	2.255	1.129	1.485	1.143	1.127	40.0	55.0
160.0	4.367	8.741	2.255	1.129	1.485	1.143	1.127	40.0	55.0
162.0	4.367	8.740	2.255	1.129	1.485	1.143	1.127	40.0	55.0
164.0	4.367	8.739	2.255	1.129	1.485	1.143	1.127	40.0	55.0
166.0	4.367	8.739	2.255	1.128	1.486	1.143	1.127	40.0	55.0
168.0	4.367	8.738	2.254	1.128	1.486	1.143	1.127	40.0	55.0
170.0	4.367	8.738	2.254	1.128	1.486	1.143	1.127	40.0	55.0
172.0	4.367	8.737	2.254	1.128	1.486	1.143	1.127	40.0	55.0
174.0	4.367	8.737	2.254	1.127	1.486	1.143	1.127	40.0	55.0
176.0	4.367	8.737	2.254	1.127	1.486	1.143	1.127	40.0	55.0
178.0	4.367	8.737	2.254	1.127	1.486	1.143	1.127	40.0	55.0
180.0	4.367	8.737	2.254	1.126	1.486	1.143	1.127	40.0	55.0

CALCULATED FINAL CONDITIONS

F= 3.397, B1= 2.254, B2= 1.126, CF= 0.02898, C1= 0.04367

C2= 0.08737, TF= 87.5, TS1= 220.4, T1= 187.1, S1= 1.486

APPENDIX 9

CONSEQUENCES OF ERRORS IN THE HEAT TRANSFER COEFFICIENTS AND HEAT LOSSES

As mentioned in Chapter VII, the heat transfer coefficients and heat losses calculated from the adjusted experimental data showed a fair degree of scatter (up to 25%). In order to determine if changes in these parameters, within this scatter range, would affect the transient behavior to any great degree 4 computer runs of experiment 4 were performed where the 2 heat transfer coefficients and the 2 heat losses were each increased by 25% over the values obtained by the above-mentioned procedure.

Comparison of the results for these 4 runs with the normal results in Appendix 8 shows that with respect to the product composition there is very little difference. In fact, the only parameter significantly affected is the first effect temperature.

Thus, it appears that it is unnecessary to take into account changes in these parameters during the course of an experiment since based upon experimental data these changes never exceeded 25%. Consequently, the heat transfer coefficient and heat losses were assumed constant for each experiment and were calculated in the manner described in Chapter VII.

EXPERIMENT 4

CLOSED LOOP RESPONSE TO A STEP UP IN FEED RATE
EFFECT OF INCREASIND UA1 BY 25 PERCENT

INPUT DATA

INITIAL CONDITIONS
F= 2.430, B1= 1.690, B2= 0.980, CF= 0.03020, C1= 0.04340
C2= 0.07510, TF= 88.5, TS1= 201.0, T1= 184.0, T2= 149.5
HSI= 1175.1

FINAL CONDITIONS
F= 2.930, B1= 2.050, B2= 1.180, CF= 0.03020, C1= 0.04320
C2= 0.07510, TF= 93.0, TS1= 211.0, T1= 190.0, T2= 149.5
HSI= 1175.1

CALCULATED PARAMETERS
UA1= 55.57, UA2= 20.92, HL2= 13.98, HL3= 55.91

CONTROLLER SETTINGS
KL1= 80.0, KL2= 175.0, KC2= 130.0, TL1= 6.0, TL2= 6.0
TC2= 7.0, TDC2= 5.0

CALCULATED INITIAL CONDITIONS
F= 2.431, B1= 1.691, B2= 0.978, CF= 0.03021, C1= 0.04344
C2= 0.07507, TF= 90.8, TS1= 197.5, T1= 183.8, SI= 0.948

EXPERIMENT 4

CLOSED LOOP RESPONSE TO A STEP UP IN FEED RATE
EFFECT OF INCREASIND UA1 BY 25 PERCENT

INPUT DATA

INITIAL CONDITIONS
F= 2.430, B1= 1.690, B2= 0.980, CF= 0.03020, C1= 0.04340
C2= 0.07510, TF= 88.5, TS1= 201.0, T1= 184.0, T2= 149.5
HS1= 1175.1

FINAL CONDITIONS
F= 2.930, B1= 2.050, B2= 1.180, CF= 0.03020, C1= 0.04320
C2= 0.07510, TF= 93.0, TS1= 211.0, T1= 190.0, T2= 149.5
HS1= 1175.1

CALCULATED PARAMETERS
UA1= 55.57, UA2= 20.92, HL2= 13.98, HL3= 55.91

CONTROLLER SETTINGS
KL1= 80.0, KL2= 175.0, KC2= 130.0, TL1= 6.0, TL2= 6.0
TC2= 7.0, TDC2= 5.0

CALCULATED INITIAL CONDITIONS
F= 2.431, B1= 1.691, B2= 0.978, CF= 0.03021, C1= 0.04344
C2= 0.07507, TF= 90.8, TS1= 197.5, T1= 183.8, S1= 0.948

TIME	C1	C2	B1	B2	SI	O1	O2	L1	L2
-2.0	4.344	7.507	1.691	0.978	0.948	0.741	0.712	40.0	55.0
-0.0	4.344	7.507	1.691	0.978	0.948	0.741	0.712	40.0	55.0
2.0	4.311	7.489	1.807	0.992	0.964	0.719	0.695	44.2	55.6
4.0	4.278	7.440	1.929	1.036	0.983	0.723	0.702	47.7	57.2
6.0	4.251	7.373	2.038	1.107	1.002	0.736	0.718	50.0	59.4
8.0	4.230	7.296	2.128	1.200	1.022	0.752	0.738	51.0	61.4
10.0	4.214	7.218	2.199	1.308	1.043	0.770	0.758	51.1	63.1
12.0	4.204	7.143	2.251	1.417	1.065	0.788	0.779	50.3	64.1
14.0	4.198	7.075	2.284	1.514	1.086	0.806	0.800	48.9	64.2
16.0	4.197	7.018	2.300	1.587	1.108	0.825	0.820	47.1	63.5
18.0	4.199	6.973	2.299	1.626	1.128	0.843	0.839	45.0	62.1
20.0	4.205	6.943	2.284	1.631	1.147	0.860	0.857	42.9	60.2
22.0	4.214	6.929	2.256	1.603	1.164	0.876	0.873	40.7	58.0
24.0	4.225	6.930	2.219	1.549	1.179	0.890	0.887	38.8	55.7
26.0	4.239	6.947	2.175	1.478	1.192	0.903	0.898	37.1	53.6
28.0	4.253	6.978	2.128	1.396	1.203	0.913	0.907	35.8	51.6
30.0	4.268	7.024	2.079	1.310	1.211	0.922	0.914	34.9	50.0
32.0	4.283	7.081	2.033	1.226	1.216	0.928	0.919	34.4	48.7
34.0	4.298	7.147	1.992	1.146	1.219	0.932	0.922	34.3	47.7
36.0	4.312	7.219	1.958	1.074	1.220	0.934	0.923	34.5	47.1
38.0	4.325	7.295	1.932	1.011	1.219	0.935	0.922	35.1	46.9
40.0	4.336	7.371	1.916	0.960	1.217	0.933	0.921	35.8	47.1
42.0	4.345	7.444	1.908	0.921	1.212	0.931	0.918	36.7	47.6
44.0	4.353	7.512	1.909	0.894	1.207	0.927	0.914	37.7	48.5
46.0	4.359	7.572	1.917	0.879	1.202	0.923	0.910	38.6	49.7
48.0	4.364	7.623	1.930	0.877	1.195	0.918	0.905	39.6	51.1
50.0	4.367	7.664	1.947	0.887	1.189	0.912	0.900	40.4	52.7
52.0	4.368	7.695	1.966	0.908	1.182	0.907	0.895	41.0	54.3
54.0	4.368	7.716	1.986	0.941	1.175	0.901	0.890	41.6	56.0
56.0	4.367	7.728	2.006	0.983	1.169	0.896	0.885	41.9	57.5
58.0	4.364	7.731	2.025	1.032	1.163	0.890	0.881	42.2	58.8
60.0	4.361	7.727	2.042	1.085	1.158	0.885	0.876	42.3	59.8
62.0	4.357	7.717	2.057	1.140	1.153	0.881	0.872	42.3	60.4
64.0	4.353	7.703	2.070	1.192	1.149	0.877	0.868	42.2	60.7
66.0	4.348	7.684	2.079	1.238	1.146	0.874	0.865	42.0	60.6
68.0	4.343	7.663	2.087	1.275	1.143	0.871	0.863	41.7	60.3
70.0	4.338	7.640	2.091	1.302	1.141	0.869	0.861	41.4	59.6
72.0	4.333	7.617	2.094	1.319	1.140	0.867	0.859	41.1	58.8
74.0	4.329	7.593	2.094	1.325	1.139	0.866	0.858	40.8	57.9
76.0	4.324	7.571	2.093	1.323	1.139	0.866	0.857	40.5	57.0
78.0	4.321	7.550	2.091	1.314	1.139	0.866	0.857	40.3	56.2
80.0	4.317	7.531	2.087	1.300	1.140	0.866	0.857	40.0	55.4
82.0	4.314	7.513	2.083	1.283	1.141	0.867	0.857	39.8	54.7
84.0	4.311	7.498	2.078	1.264	1.142	0.867	0.858	39.7	54.2
86.0	4.309	7.486	2.073	1.245	1.143	0.868	0.859	39.6	53.8
88.0	4.308	7.476	2.068	1.227	1.145	0.870	0.860	39.5	53.6
90.0	4.306	7.468	2.064	1.211	1.146	0.871	0.861	39.4	53.4
92.0	4.306	7.462	2.059	1.197	1.148	0.872	0.862	39.4	53.4
94.0	4.305	7.458	2.056	1.184	1.149	0.874	0.864	39.4	53.4
96.0	4.305	7.456	2.053	1.175	1.151	0.875	0.865	39.5	53.5
98.0	4.305	7.455	2.050	1.167	1.152	0.876	0.866	39.5	53.7

TIME	C1	C2	B1	B2	S1	O1	O2	L1	L2
-2.0	4.344	7.507	1.691	0.978	0.948	0.741	0.712	40.0	55.0
-0.0	4.344	7.507	1.691	0.978	0.948	0.741	0.712	40.0	55.0
2.0	4.311	7.489	1.807	0.992	0.964	0.719	0.695	44.2	55.6
4.0	4.278	7.440	1.929	1.036	0.983	0.723	0.702	47.7	57.2
6.0	4.251	7.373	2.038	1.107	1.002	0.736	0.718	50.0	59.4
8.0	4.230	7.296	2.128	1.200	1.022	0.752	0.738	51.0	61.4
10.0	4.214	7.218	2.199	1.308	1.043	0.770	0.758	51.1	63.1
12.0	4.204	7.143	2.251	1.417	1.065	0.788	0.779	50.3	64.1
14.0	4.198	7.075	2.284	1.514	1.086	0.806	0.800	48.9	64.2
16.0	4.197	7.018	2.300	1.587	1.108	0.825	0.820	47.1	63.5
18.0	4.199	6.973	2.299	1.626	1.128	0.843	0.839	45.0	62.1
20.0	4.205	6.943	2.284	1.631	1.147	0.860	0.857	42.9	60.2
22.0	4.214	6.929	2.256	1.603	1.164	0.876	0.873	40.7	58.0
24.0	4.225	6.930	2.219	1.549	1.179	0.890	0.887	38.8	55.7
26.0	4.239	6.947	2.175	1.478	1.192	0.903	0.898	37.1	53.6
28.0	4.253	6.978	2.128	1.396	1.203	0.913	0.907	35.8	51.6
30.0	4.268	7.024	2.079	1.310	1.211	0.922	0.914	34.9	50.0
32.0	4.283	7.081	2.033	1.226	1.216	0.928	0.919	34.4	48.7
34.0	4.298	7.147	1.992	1.146	1.219	0.932	0.922	34.3	47.7
36.0	4.312	7.219	1.958	1.074	1.220	0.934	0.923	34.5	47.1
38.0	4.325	7.295	1.932	1.011	1.219	0.935	0.922	35.1	46.9
40.0	4.336	7.371	1.916	0.960	1.217	0.933	0.921	35.8	47.1
42.0	4.345	7.444	1.908	0.921	1.212	0.931	0.918	36.7	47.6
44.0	4.353	7.512	1.909	0.894	1.207	0.927	0.914	37.7	48.5
46.0	4.359	7.572	1.917	0.879	1.202	0.923	0.910	38.6	49.7
48.0	4.364	7.623	1.930	0.877	1.195	0.918	0.905	39.6	51.1
50.0	4.367	7.664	1.947	0.887	1.189	0.912	0.900	40.4	52.7
52.0	4.368	7.695	1.966	0.908	1.182	0.907	0.895	41.0	54.3
54.0	4.368	7.716	1.986	0.941	1.175	0.901	0.890	41.6	56.0
56.0	4.367	7.728	2.006	0.983	1.169	0.896	0.885	41.9	57.5
58.0	4.364	7.731	2.025	1.032	1.163	0.890	0.881	42.2	58.8
60.0	4.361	7.727	2.042	1.085	1.158	0.885	0.876	42.3	59.8
62.0	4.357	7.717	2.057	1.140	1.153	0.881	0.872	42.3	60.4
64.0	4.353	7.703	2.070	1.192	1.149	0.877	0.868	42.2	60.7
66.0	4.348	7.684	2.079	1.238	1.146	0.874	0.865	42.0	60.6
68.0	4.343	7.663	2.087	1.275	1.143	0.871	0.863	41.7	60.3
70.0	4.338	7.640	2.091	1.302	1.141	0.869	0.861	41.4	59.6
72.0	4.333	7.617	2.094	1.319	1.140	0.867	0.859	41.1	58.8
74.0	4.329	7.593	2.094	1.325	1.139	0.866	0.858	40.8	57.9
76.0	4.324	7.571	2.093	1.323	1.139	0.866	0.857	40.5	57.0
78.0	4.321	7.550	2.091	1.314	1.139	0.866	0.857	40.3	56.2
80.0	4.317	7.531	2.087	1.300	1.140	0.866	0.857	40.0	55.4
82.0	4.314	7.513	2.083	1.283	1.141	0.867	0.857	39.8	54.7
84.0	4.311	7.498	2.078	1.264	1.142	0.867	0.858	39.7	54.2
86.0	4.309	7.486	2.073	1.245	1.143	0.868	0.859	39.6	53.8
88.0	4.308	7.476	2.068	1.227	1.145	0.870	0.860	39.5	53.6
90.0	4.306	7.468	2.064	1.211	1.146	0.871	0.861	39.4	53.4
92.0	4.306	7.462	2.059	1.197	1.148	0.872	0.862	39.4	53.4
94.0	4.305	7.458	2.056	1.184	1.149	0.874	0.864	39.4	53.4
96.0	4.305	7.456	2.053	1.175	1.151	0.875	0.865	39.5	53.5
98.0	4.305	7.455	2.050	1.167	1.152	0.876	0.866	39.5	53.7

..CONTD

TIME	C1	C2	B1	B2	SI	O1	O2	L1	L2
100.0	4.306	7.456	2.048	1.162	1.154	0.877	0.868	39.6	53.9
102.0	4.306	7.458	2.047	1.158	1.155	0.879	0.869	39.6	54.1
104.0	4.307	7.460	2.046	1.156	1.156	0.880	0.870	39.7	54.3
106.0	4.308	7.463	2.045	1.156	1.157	0.881	0.871	39.8	54.5
108.0	4.309	7.467	2.045	1.157	1.158	0.882	0.872	39.8	54.6
110.0	4.311	7.471	2.045	1.158	1.159	0.882	0.872	39.9	54.8
112.0	4.312	7.475	2.045	1.160	1.160	0.883	0.873	39.9	54.9
114.0	4.313	7.479	2.045	1.163	1.160	0.883	0.874	39.9	55.0
116.0	4.314	7.483	2.045	1.165	1.160	0.884	0.874	40.0	55.1
118.0	4.315	7.488	2.046	1.167	1.161	0.884	0.874	40.0	55.2
120.0	4.316	7.492	2.046	1.169	1.161	0.884	0.875	40.0	55.2
122.0	4.317	7.496	2.046	1.171	1.161	0.884	0.875	40.0	55.2
124.0	4.318	7.499	2.046	1.173	1.161	0.884	0.875	40.0	55.2
126.0	4.319	7.503	2.047	1.174	1.161	0.884	0.875	40.0	55.2
128.0	4.320	7.506	2.047	1.175	1.160	0.884	0.875	40.0	55.2
130.0	4.320	7.509	2.047	1.175	1.160	0.884	0.874	40.0	55.1
132.0	4.321	7.512	2.048	1.176	1.160	0.884	0.874	40.0	55.1
134.0	4.321	7.514	2.048	1.176	1.159	0.883	0.874	40.0	55.1
136.0	4.321	7.516	2.048	1.176	1.159	0.883	0.874	40.0	55.1
138.0	4.321	7.517	2.049	1.176	1.159	0.883	0.873	40.0	55.1
140.0	4.321	7.518	2.049	1.177	1.158	0.882	0.873	40.0	55.1
142.0	4.321	7.519	2.049	1.177	1.158	0.882	0.873	40.0	55.0
144.0	4.321	7.519	2.050	1.177	1.157	0.882	0.872	40.0	55.0
146.0	4.321	7.520	2.050	1.178	1.157	0.881	0.872	40.1	55.0
148.0	4.321	7.519	2.050	1.178	1.157	0.881	0.872	40.1	55.1
150.0	4.321	7.519	2.051	1.179	1.156	0.881	0.871	40.1	55.1
152.0	4.320	7.518	2.051	1.180	1.156	0.881	0.871	40.1	55.1
154.0	4.320	7.517	2.051	1.180	1.156	0.880	0.871	40.1	55.1
156.0	4.320	7.516	2.052	1.181	1.156	0.880	0.871	40.0	55.1
158.0	4.319	7.515	2.052	1.181	1.156	0.880	0.870	40.0	55.1
160.0	4.319	7.514	2.052	1.182	1.155	0.880	0.870	40.0	55.1
162.0	4.319	7.513	2.052	1.183	1.155	0.880	0.870	40.0	55.1
164.0	4.319	7.512	2.052	1.183	1.155	0.880	0.870	40.0	55.1
166.0	4.318	7.510	2.052	1.183	1.155	0.880	0.870	40.0	55.1
168.0	4.318	7.509	2.052	1.183	1.155	0.880	0.870	40.0	55.0
170.0	4.318	7.508	2.052	1.183	1.155	0.880	0.870	40.0	55.0
172.0	4.318	7.507	2.052	1.183	1.155	0.880	0.870	40.0	55.0
174.0	4.317	7.506	2.052	1.183	1.156	0.880	0.870	40.0	55.0
176.0	4.317	7.505	2.052	1.183	1.156	0.880	0.870	40.0	55.0
178.0	4.317	7.505	2.052	1.183	1.156	0.880	0.870	40.0	55.0
180.0	4.317	7.504	2.052	1.182	1.156	0.880	0.871	40.0	55.0

CALCULATED FINAL CONDITIONS
F= 2.932, B1= 2.052, B2= 1.182, CF= 0.03021, C1= 0.04317
C2= 0.07504, TF= 90.8, TS1= 206.8, T1= 190.2, SI= 1.156

..CONTD

TIME	C1	C2	B1	B2	S1	O1	O2	L1	L2
100.0	4.306	7.456	2.048	1.162	1.154	0.877	0.868	39.6	53.9
102.0	4.306	7.458	2.047	1.158	1.155	0.879	0.869	39.6	54.1
104.0	4.307	7.460	2.046	1.156	1.156	0.880	0.870	39.7	54.3
106.0	4.308	7.463	2.045	1.156	1.157	0.881	0.871	39.8	54.5
108.0	4.309	7.467	2.045	1.157	1.158	0.882	0.872	39.8	54.6
110.0	4.311	7.471	2.045	1.158	1.159	0.882	0.872	39.9	54.8
112.0	4.312	7.475	2.045	1.160	1.160	0.883	0.873	39.9	54.9
114.0	4.313	7.479	2.045	1.163	1.160	0.883	0.874	39.9	55.0
116.0	4.314	7.483	2.045	1.165	1.160	0.884	0.874	40.0	55.1
118.0	4.315	7.488	2.046	1.167	1.161	0.884	0.874	40.0	55.2
120.0	4.316	7.492	2.046	1.169	1.161	0.884	0.875	40.0	55.2
122.0	4.317	7.496	2.046	1.171	1.161	0.884	0.875	40.0	55.2
124.0	4.318	7.499	2.046	1.173	1.161	0.884	0.875	40.0	55.2
126.0	4.319	7.503	2.047	1.174	1.161	0.884	0.875	40.0	55.2
128.0	4.320	7.506	2.047	1.175	1.160	0.884	0.875	40.0	55.2
130.0	4.320	7.509	2.047	1.175	1.160	0.884	0.874	40.0	55.1
132.0	4.321	7.512	2.048	1.176	1.160	0.884	0.874	40.0	55.1
134.0	4.321	7.514	2.048	1.176	1.159	0.883	0.874	40.0	55.1
136.0	4.321	7.516	2.048	1.176	1.159	0.883	0.874	40.0	55.1
138.0	4.321	7.517	2.049	1.176	1.159	0.883	0.873	40.0	55.1
140.0	4.321	7.518	2.049	1.177	1.158	0.882	0.873	40.0	55.1
142.0	4.321	7.519	2.049	1.177	1.158	0.882	0.873	40.0	55.0
144.0	4.321	7.519	2.050	1.177	1.157	0.882	0.872	40.0	55.0
146.0	4.321	7.520	2.050	1.178	1.157	0.881	0.872	40.1	55.0
148.0	4.321	7.519	2.050	1.178	1.157	0.881	0.872	40.1	55.1
150.0	4.321	7.519	2.051	1.179	1.156	0.881	0.871	40.1	55.1
152.0	4.320	7.518	2.051	1.180	1.156	0.881	0.871	40.1	55.1
154.0	4.320	7.517	2.051	1.180	1.156	0.880	0.871	40.1	55.1
156.0	4.320	7.516	2.052	1.181	1.156	0.880	0.871	40.0	55.1
158.0	4.319	7.515	2.052	1.181	1.156	0.880	0.870	40.0	55.1
160.0	4.319	7.514	2.052	1.182	1.155	0.880	0.870	40.0	55.1
162.0	4.319	7.513	2.052	1.183	1.155	0.880	0.870	40.0	55.1
164.0	4.319	7.512	2.052	1.183	1.155	0.880	0.870	40.0	55.1
166.0	4.318	7.510	2.052	1.183	1.155	0.880	0.870	40.0	55.1
168.0	4.318	7.509	2.052	1.183	1.155	0.880	0.870	40.0	55.0
170.0	4.318	7.508	2.052	1.183	1.155	0.880	0.870	40.0	55.0
172.0	4.318	7.507	2.052	1.183	1.155	0.880	0.870	40.0	55.0
174.0	4.317	7.506	2.052	1.183	1.156	0.880	0.870	40.0	55.0
176.0	4.317	7.505	2.052	1.183	1.156	0.880	0.870	40.0	55.0
178.0	4.317	7.505	2.052	1.183	1.156	0.880	0.870	40.0	55.0
180.0	4.317	7.504	2.052	1.182	1.156	0.880	0.871	40.0	55.0

CALCULATED FINAL CONDITIONS

F= 2.932, B1= 2.052, B2= 1.182, CF= 0.03021, C1= 0.04317

C2= 0.07504, TF= 90.8, TS1= 206.8, T1= 190.2, S1= 1.156

EXPERIMENT 4

CLOSED LOOP RESPONSE TO A STEP UP IN FEED RATE
EFFECT OF INCREASING UA2 BY 25 PERCENT

INPUT DATA

INITIAL CONDITIONS
F= 2.430, B1= 1.690, B2= 0.980, CF= 0.03020, C1= 0.04340
C2= 0.07510, TF= 88.5, TS1= 201.0, T1= 184.0, T2= 149.5
HSI= 1175.1

FINAL CONDITIONS
F= 2.930, B1= 2.050, B2= 1.180, CF= 0.03020, C1= 0.04320
C2= 0.07510, TF= 93.0, TS1= 211.0, T1= 190.0, T2= 149.5
HSI= 1175.1

CALCULATED PARAMETERS
UA1= 55.57, UA2= 20.92, HL2= 13.98, HL3= 55.91

CONTROLLER SETTINGS
KL1= 80.0, KL2= 175.0, KC2= 130.0, TL1= 6.0, TL2= 6.0
TC2= 7.0, TDC2= 5.0

CALCULATED INITIAL CONDITIONS
F= 2.431, B1= 1.687, B2= 0.978, CF= 0.03021, C1= 0.04354
C2= 0.07507, TF= 90.8, TS1= 194.2, T1= 177.2, SI= 0.936

EXPERIMENT 4

CLOSED LOOP RESPONSE TO A STEP UP IN FEED RATE
EFFECT OF INCREASING UA2 BY 25 PERCENT

INPUT DATA

INITIAL CONDITIONS
F= 2.430, B1= 1.690, B2= 0.980, CF= 0.03020, C1= 0.04340
C2= 0.07510, TF= 88.5, TS1= 201.0, T1= 184.0, T2= 149.5
HS1= 1175.1

FINAL CONDITIONS
F= 2.930, B1= 2.050, B2= 1.180, CF= 0.03020, C1= 0.04320
C2= 0.07510, TF= 93.0, TS1= 211.0, T1= 190.0, T2= 149.5
HS1= 1175.1

CALCULATED PARAMETERS
UA1= 55.57, UA2= 20.92, HL2= 13.98, HL3= 55.91

CONTROLLER SETTINGS
KL1= 80.0, KL2= 175.0, KC2= 130.0, TL1= 6.0, TL2= 6.0
TC2= 7.0, TDC2= 5.0

CALCULATED INITIAL CONDITIONS
F= 2.431, B1= 1.687, B2= 0.978, CF= 0.03021, C1= 0.04354
C2= 0.07507, TF= 90.8, TS1= 194.2, T1= 177.2, S1= 0.936

TIME	C1	C2	B1	B2	SI	O1	O2	L1	L2
-2.0	4.354	7.507	1.687	0.978	0.936	0.745	0.708	40.0	55.0
-0.0	4.354	7.507	1.687	0.978	0.936	0.745	0.708	40.0	55.0
2.0	4.321	7.489	1.803	0.992	0.953	0.723	0.691	44.2	55.6
4.0	4.288	7.440	1.926	1.036	0.971	0.730	0.699	47.7	57.3
6.0	4.262	7.374	2.033	1.107	0.990	0.745	0.717	49.9	59.3
8.0	4.241	7.299	2.122	1.199	1.010	0.762	0.737	50.9	61.4
10.0	4.227	7.222	2.192	1.305	1.031	0.779	0.757	50.9	63.0
12.0	4.217	7.149	2.243	1.412	1.052	0.798	0.778	50.2	64.0
14.0	4.212	7.084	2.275	1.508	1.074	0.817	0.798	48.8	64.1
16.0	4.211	7.029	2.289	1.579	1.094	0.835	0.818	46.9	63.4
18.0	4.215	6.986	2.288	1.617	1.114	0.853	0.837	44.9	62.0
20.0	4.221	6.959	2.271	1.620	1.133	0.870	0.855	42.7	60.0
22.0	4.231	6.946	2.243	1.592	1.149	0.886	0.870	40.6	57.9
24.0	4.242	6.949	2.206	1.538	1.164	0.900	0.884	38.7	55.6
26.0	4.256	6.968	2.162	1.467	1.176	0.912	0.895	37.1	53.5
28.0	4.270	7.001	2.114	1.385	1.186	0.922	0.904	35.8	51.6
30.0	4.285	7.048	2.067	1.300	1.193	0.930	0.910	34.9	49.9
32.0	4.300	7.106	2.021	1.216	1.198	0.935	0.915	34.5	48.6
34.0	4.315	7.172	1.981	1.137	1.201	0.939	0.917	34.4	47.7
36.0	4.328	7.244	1.949	1.067	1.201	0.940	0.917	34.7	47.1
38.0	4.341	7.319	1.925	1.006	1.199	0.940	0.916	35.2	47.0
40.0	4.351	7.394	1.910	0.957	1.196	0.938	0.914	36.0	47.2
42.0	4.360	7.464	1.904	0.919	1.192	0.935	0.910	36.9	47.8
44.0	4.367	7.529	1.906	0.894	1.187	0.931	0.906	37.9	48.7
46.0	4.373	7.586	1.915	0.882	1.181	0.926	0.902	38.8	49.9
48.0	4.376	7.634	1.929	0.882	1.174	0.920	0.897	39.7	51.4
50.0	4.378	7.671	1.947	0.894	1.168	0.915	0.892	40.5	53.0
52.0	4.379	7.698	1.966	0.918	1.161	0.909	0.886	41.2	54.7
54.0	4.378	7.715	1.987	0.953	1.155	0.903	0.881	41.7	56.3
56.0	4.377	7.723	2.007	0.996	1.149	0.898	0.876	42.0	57.8
58.0	4.374	7.724	2.025	1.047	1.143	0.893	0.872	42.2	59.0
60.0	4.370	7.717	2.042	1.101	1.138	0.888	0.867	42.3	59.9
62.0	4.366	7.705	2.056	1.155	1.134	0.884	0.864	42.2	60.5
64.0	4.362	7.688	2.068	1.206	1.131	0.881	0.860	42.1	60.7
66.0	4.357	7.668	2.077	1.250	1.128	0.878	0.857	41.9	60.6
68.0	4.352	7.646	2.084	1.285	1.126	0.876	0.855	41.6	60.1
70.0	4.347	7.623	2.088	1.310	1.124	0.874	0.854	41.3	59.4
72.0	4.343	7.600	2.089	1.323	1.123	0.873	0.852	41.0	58.6
74.0	4.338	7.577	2.089	1.327	1.123	0.872	0.852	40.7	57.7
76.0	4.334	7.556	2.087	1.322	1.123	0.872	0.851	40.4	56.8
78.0	4.331	7.536	2.084	1.311	1.123	0.872	0.852	40.2	55.9
80.0	4.328	7.518	2.079	1.295	1.124	0.873	0.852	39.9	55.2
82.0	4.325	7.503	2.075	1.277	1.125	0.874	0.853	39.7	54.5
84.0	4.323	7.490	2.069	1.257	1.127	0.875	0.854	39.6	54.0
86.0	4.321	7.479	2.064	1.238	1.128	0.876	0.855	39.5	53.7
88.0	4.320	7.471	2.059	1.220	1.129	0.877	0.856	39.4	53.4
90.0	4.319	7.465	2.055	1.203	1.131	0.878	0.857	39.4	53.3
92.0	4.318	7.461	2.051	1.189	1.132	0.880	0.858	39.4	53.3
94.0	4.318	7.459	2.047	1.177	1.134	0.881	0.859	39.4	53.4
96.0	4.318	7.458	2.044	1.168	1.135	0.882	0.861	39.5	53.5
98.0	4.319	7.459	2.042	1.161	1.137	0.883	0.862	39.5	53.7

TIME	C1	C2	B1	B2	S1	O1	O2	L1	L2
-2.0	4.354	7.507	1.687	0.978	0.936	0.745	0.708	40.0	55.0
-0.0	4.354	7.507	1.687	0.978	0.936	0.745	0.708	40.0	55.0
2.0	4.321	7.489	1.803	0.992	0.953	0.723	0.691	44.2	55.6
4.0	4.288	7.440	1.926	1.036	0.971	0.730	0.699	47.7	57.3
6.0	4.262	7.374	2.033	1.107	0.990	0.745	0.717	49.9	59.3
8.0	4.241	7.299	2.122	1.199	1.010	0.762	0.737	50.9	61.4
10.0	4.227	7.222	2.192	1.305	1.031	0.779	0.757	50.9	63.0
12.0	4.217	7.149	2.243	1.412	1.052	0.798	0.778	50.2	64.0
14.0	4.212	7.084	2.275	1.508	1.074	0.817	0.798	48.8	64.1
16.0	4.211	7.029	2.289	1.579	1.094	0.835	0.818	46.9	63.4
18.0	4.215	6.986	2.288	1.617	1.114	0.853	0.837	44.9	62.0
20.0	4.221	6.959	2.271	1.620	1.133	0.870	0.855	42.7	60.0
22.0	4.231	6.946	2.243	1.592	1.149	0.886	0.870	40.6	57.9
24.0	4.242	6.949	2.206	1.538	1.164	0.900	0.884	38.7	55.6
26.0	4.256	6.968	2.162	1.467	1.176	0.912	0.895	37.1	53.5
28.0	4.270	7.001	2.114	1.385	1.186	0.922	0.904	35.8	51.6
30.0	4.285	7.048	2.067	1.300	1.193	0.930	0.910	34.9	49.9
32.0	4.300	7.106	2.021	1.216	1.198	0.935	0.915	34.5	48.6
34.0	4.315	7.172	1.981	1.137	1.201	0.939	0.917	34.4	47.7
36.0	4.328	7.244	1.949	1.067	1.201	0.940	0.917	34.7	47.1
38.0	4.341	7.319	1.925	1.006	1.199	0.940	0.916	35.2	47.0
40.0	4.351	7.394	1.910	0.957	1.196	0.938	0.914	36.0	47.2
42.0	4.360	7.464	1.904	0.919	1.192	0.935	0.910	36.9	47.8
44.0	4.367	7.529	1.906	0.894	1.187	0.931	0.906	37.9	48.7
46.0	4.373	7.586	1.915	0.882	1.181	0.926	0.902	38.8	49.9
48.0	4.376	7.634	1.929	0.882	1.174	0.920	0.897	39.7	51.4
50.0	4.378	7.671	1.947	0.894	1.168	0.915	0.892	40.5	53.0
52.0	4.379	7.698	1.966	0.918	1.161	0.909	0.886	41.2	54.7
54.0	4.378	7.715	1.987	0.953	1.155	0.903	0.881	41.7	56.3
56.0	4.377	7.723	2.007	0.996	1.149	0.898	0.876	42.0	57.8
58.0	4.374	7.724	2.025	1.047	1.143	0.893	0.872	42.2	59.0
60.0	4.370	7.717	2.042	1.101	1.138	0.888	0.867	42.3	59.9
62.0	4.366	7.705	2.056	1.155	1.134	0.884	0.864	42.2	60.5
64.0	4.362	7.688	2.068	1.206	1.131	0.881	0.860	42.1	60.7
66.0	4.357	7.668	2.077	1.250	1.128	0.878	0.857	41.9	60.6
68.0	4.352	7.646	2.084	1.285	1.126	0.876	0.855	41.6	60.1
70.0	4.347	7.623	2.088	1.310	1.124	0.874	0.854	41.3	59.4
72.0	4.343	7.600	2.089	1.323	1.123	0.873	0.852	41.0	58.6
74.0	4.338	7.577	2.089	1.327	1.123	0.872	0.852	40.7	57.7
76.0	4.334	7.556	2.087	1.322	1.123	0.872	0.851	40.4	56.8
78.0	4.331	7.536	2.084	1.311	1.123	0.872	0.852	40.2	55.9
80.0	4.328	7.518	2.079	1.295	1.124	0.873	0.852	39.9	55.2
82.0	4.325	7.503	2.075	1.277	1.125	0.874	0.853	39.7	54.5
84.0	4.323	7.490	2.069	1.257	1.127	0.875	0.854	39.6	54.0
86.0	4.321	7.479	2.064	1.238	1.128	0.876	0.855	39.5	53.7
88.0	4.320	7.471	2.059	1.220	1.129	0.877	0.856	39.4	53.4
90.0	4.319	7.465	2.055	1.203	1.131	0.878	0.857	39.4	53.3
92.0	4.318	7.461	2.051	1.189	1.132	0.880	0.858	39.4	53.3
94.0	4.318	7.459	2.047	1.177	1.134	0.881	0.859	39.4	53.4
96.0	4.318	7.458	2.044	1.168	1.135	0.882	0.861	39.5	53.5
98.0	4.319	7.459	2.042	1.161	1.137	0.883	0.862	39.5	53.7

..CONTD

TIME	C1	C2	B1	B2	SI	O1	O2	L1	L2
100.0	4.319	7.460	2.040	1.156	1.138	0.885	0.863	39.6	53.9
102.0	4.320	7.463	2.039	1.154	1.139	0.886	0.864	39.7	54.1
104.0	4.321	7.466	2.039	1.153	1.140	0.886	0.865	39.7	54.3
106.0	4.322	7.470	2.038	1.153	1.141	0.887	0.866	39.8	54.5
108.0	4.323	7.473	2.038	1.155	1.142	0.888	0.866	39.9	54.7
110.0	4.324	7.477	2.038	1.157	1.142	0.889	0.867	39.9	54.9
112.0	4.325	7.481	2.039	1.160	1.143	0.889	0.868	39.9	55.0
114.0	4.327	7.486	2.039	1.163	1.143	0.889	0.868	40.0	55.1
116.0	4.328	7.489	2.040	1.166	1.143	0.890	0.868	40.0	55.2
118.0	4.329	7.493	2.040	1.169	1.143	0.890	0.868	40.0	55.2
120.0	4.329	7.497	2.041	1.171	1.143	0.890	0.869	40.0	55.3
122.0	4.330	7.500	2.041	1.173	1.143	0.890	0.869	40.0	55.3
124.0	4.331	7.503	2.041	1.175	1.143	0.890	0.869	40.0	55.2
126.0	4.332	7.506	2.042	1.176	1.143	0.890	0.868	40.0	55.2
128.0	4.332	7.509	2.042	1.177	1.143	0.890	0.868	40.0	55.2
130.0	4.333	7.511	2.042	1.178	1.142	0.889	0.868	40.0	55.2
132.0	4.333	7.513	2.043	1.178	1.142	0.889	0.868	40.0	55.1
134.0	4.333	7.514	2.043	1.178	1.142	0.889	0.868	40.0	55.1
136.0	4.333	7.516	2.043	1.178	1.141	0.888	0.867	40.0	55.1
138.0	4.333	7.517	2.043	1.178	1.141	0.888	0.867	40.0	55.0
140.0	4.333	7.517	2.044	1.178	1.141	0.888	0.867	40.0	55.0
142.0	4.333	7.518	2.044	1.178	1.140	0.888	0.866	40.0	55.0
144.0	4.333	7.518	2.044	1.178	1.140	0.887	0.866	40.0	55.0
146.0	4.333	7.518	2.045	1.179	1.140	0.887	0.866	40.0	55.0
148.0	4.333	7.517	2.045	1.179	1.139	0.887	0.865	40.0	55.0
150.0	4.333	7.517	2.045	1.179	1.139	0.886	0.865	40.0	55.0
152.0	4.332	7.516	2.045	1.180	1.139	0.886	0.865	40.0	55.0
154.0	4.332	7.515	2.046	1.180	1.139	0.886	0.865	40.0	55.0
156.0	4.332	7.514	2.046	1.181	1.139	0.886	0.865	40.0	55.1
158.0	4.331	7.513	2.046	1.181	1.139	0.886	0.865	40.0	55.1
160.0	4.331	7.512	2.046	1.182	1.138	0.886	0.864	40.0	55.1
162.0	4.331	7.511	2.046	1.182	1.138	0.886	0.864	40.0	55.1
164.0	4.331	7.510	2.046	1.183	1.138	0.886	0.864	40.0	55.0
166.0	4.330	7.509	2.046	1.183	1.138	0.886	0.864	40.0	55.0
168.0	4.330	7.508	2.046	1.183	1.139	0.886	0.864	40.0	55.0
170.0	4.330	7.507	2.046	1.183	1.139	0.886	0.864	40.0	55.0
172.0	4.330	7.506	2.046	1.183	1.139	0.886	0.865	40.0	55.0
174.0	4.330	7.506	2.046	1.183	1.139	0.886	0.865	40.0	55.0
176.0	4.330	7.505	2.046	1.182	1.139	0.886	0.865	40.0	55.0
178.0	4.330	7.505	2.046	1.182	1.139	0.886	0.865	40.0	55.0
180.0	4.330	7.504	2.046	1.182	1.139	0.886	0.865	40.0	55.0

CALCULATED FINAL CONDITIONS
F= 2.932, B1= 2.046, B2= 1.182, CF= 0.03021, C1= 0.04330
C2= 0.07504, TF= 90.8, TS1= 203.0, T1= 182.5, SI= 1.139

..CONTD

TIME	C1	C2	B1	B2	S1	O1	O2	L1	L2
100.0	4.319	7.460	2.040	1.156	1.138	0.885	0.863	39.6	53.9
102.0	4.320	7.463	2.039	1.154	1.139	0.886	0.864	39.7	54.1
104.0	4.321	7.466	2.039	1.153	1.140	0.886	0.865	39.7	54.3
106.0	4.322	7.470	2.038	1.153	1.141	0.887	0.866	39.8	54.5
108.0	4.323	7.473	2.038	1.155	1.142	0.888	0.866	39.9	54.7
110.0	4.324	7.477	2.038	1.157	1.142	0.889	0.867	39.9	54.9
112.0	4.325	7.481	2.039	1.160	1.143	0.889	0.868	39.9	55.0
114.0	4.327	7.486	2.039	1.163	1.143	0.889	0.868	40.0	55.1
116.0	4.328	7.489	2.040	1.166	1.143	0.890	0.868	40.0	55.2
118.0	4.329	7.493	2.040	1.169	1.143	0.890	0.868	40.0	55.2
120.0	4.329	7.497	2.041	1.171	1.143	0.890	0.869	40.0	55.3
122.0	4.330	7.500	2.041	1.173	1.143	0.890	0.869	40.0	55.3
124.0	4.331	7.503	2.041	1.175	1.143	0.890	0.869	40.0	55.2
126.0	4.332	7.506	2.042	1.176	1.143	0.890	0.868	40.0	55.2
128.0	4.332	7.509	2.042	1.177	1.143	0.890	0.868	40.0	55.2
130.0	4.333	7.511	2.042	1.178	1.142	0.889	0.868	40.0	55.2
132.0	4.333	7.513	2.043	1.178	1.142	0.889	0.868	40.0	55.1
134.0	4.333	7.514	2.043	1.178	1.142	0.889	0.868	40.0	55.1
136.0	4.333	7.516	2.043	1.178	1.141	0.888	0.867	40.0	55.1
138.0	4.333	7.517	2.043	1.178	1.141	0.888	0.867	40.0	55.0
140.0	4.333	7.517	2.044	1.178	1.141	0.888	0.867	40.0	55.0
142.0	4.333	7.518	2.044	1.178	1.140	0.888	0.866	40.0	55.0
144.0	4.333	7.518	2.044	1.178	1.140	0.887	0.866	40.0	55.0
146.0	4.333	7.518	2.045	1.179	1.140	0.887	0.866	40.0	55.0
148.0	4.333	7.517	2.045	1.179	1.139	0.887	0.865	40.0	55.0
150.0	4.333	7.517	2.045	1.179	1.139	0.886	0.865	40.0	55.0
152.0	4.332	7.516	2.045	1.180	1.139	0.886	0.865	40.0	55.0
154.0	4.332	7.515	2.046	1.180	1.139	0.886	0.865	40.0	55.0
156.0	4.332	7.514	2.046	1.181	1.139	0.886	0.865	40.0	55.1
158.0	4.331	7.513	2.046	1.181	1.139	0.886	0.865	40.0	55.1
160.0	4.331	7.512	2.046	1.182	1.138	0.886	0.864	40.0	55.1
162.0	4.331	7.511	2.046	1.182	1.138	0.886	0.864	40.0	55.1
164.0	4.331	7.510	2.046	1.183	1.138	0.886	0.864	40.0	55.0
166.0	4.330	7.509	2.046	1.183	1.138	0.886	0.864	40.0	55.0
168.0	4.330	7.508	2.046	1.183	1.139	0.886	0.864	40.0	55.0
170.0	4.330	7.507	2.046	1.183	1.139	0.886	0.864	40.0	55.0
172.0	4.330	7.506	2.046	1.183	1.139	0.886	0.865	40.0	55.0
174.0	4.330	7.506	2.046	1.183	1.139	0.886	0.865	40.0	55.0
176.0	4.330	7.505	2.046	1.182	1.139	0.886	0.865	40.0	55.0
178.0	4.330	7.505	2.046	1.182	1.139	0.886	0.865	40.0	55.0
180.0	4.330	7.504	2.046	1.182	1.139	0.886	0.865	40.0	55.0

CALCULATED FINAL CONDITIONS

F= 2.932, B1= 2.046, B2= 1.182, CF= 0.03021, C1= 0.04330

C2= 0.07504, TF= 90.8, TS1= 203.0, T1= 182.5, S1= 1.139

EXPERIMENT 4

CLOSED LOOP RESPONSE TO A STEP UP IN FEED RATE
EFFECT OF INCREASING HL2 BY 25 PERCENT

INPUT DATA

INITIAL CONDITIONS
F= 2.430, B1= 1.690, B2= 0.980, CF= 0.03020, C1= 0.04340
C2= 0.07510, TF= 88.5, TS1= 201.0, T1= 184.0, T2= 149.5
HSI= 1175.1

FINAL CONDITIONS
F= 2.930, B1= 2.050, B2= 1.180, CF= 0.03020, C1= 0.04320
C2= 0.07510, TF= 93.0, TS1= 211.0, T1= 190.0, T2= 149.5
HSI= 1175.1

CALCULATED PARAMETERS
UA1= 55.57, UA2= 20.92, HL2= 13.98, HL3= 55.91

CONTROLLER SETTINGS
KL1= 80.0, KL2= 175.0, KC2= 130.0, TL1= 6.0, TL2= 6.0
TC2= 7.0, TDC2= 5.0

CALCULATED INITIAL CONDITIONS
F= 2.431, B1= 1.689, B2= 0.978, CF= 0.03021, C1= 0.04349
C2= 0.07507, TF= 90.8, TS1= 200.9, T1= 183.7, SI= 0.952

EXPERIMENT 4

CLOSED LOOP RESPONSE TO A STEP UP IN FEED RATE
EFFECT OF INCREASING HL2 BY 25 PERCENT

INPUT DATA

INITIAL CONDITIONS
F= 2.430, B1= 1.690, B2= 0.980, CF= 0.03020, C1= 0.04340
C2= 0.07510, TF= 88.5, TS1= 201.0, T1= 184.0, T2= 149.5
HS1= 1175.1

FINAL CONDITIONS
F= 2.930, B1= 2.050, B2= 1.180, CF= 0.03020, C1= 0.04320
C2= 0.07510, TF= 93.0, TS1= 211.0, T1= 190.0, T2= 149.5
HS1= 1175.1

CALCULATED PARAMETERS
UA1= 55.57, UA2= 20.92, HL2= 13.98, HL3= 55.91

CONTROLLER SETTINGS
KL1= 80.0, KL2= 175.0, KC2= 130.0, TL1= 6.0, TL2= 6.0
TC2= 7.0, TDC2= 5.0

CALCULATED INITIAL CONDITIONS
F= 2.431, B1= 1.689, B2= 0.978, CF= 0.03021, C1= 0.04349
C2= 0.07507, TF= 90.8, TS1= 200.9, T1= 183.7, S1= 0.952

TIME	C1	C2	B1	B2	SI	O1	O2	L1	L2
-2.0	4.349	7.507	1.689	0.978	0.952	0.742	0.711	40.0	55.0
-0.0	4.349	7.507	1.689	0.978	0.952	0.742	0.711	40.0	55.0
2.0	4.316	7.489	1.805	0.992	0.969	0.721	0.694	44.2	55.6
4.0	4.283	7.440	1.928	1.036	0.988	0.725	0.700	47.7	57.2
6.0	4.255	7.373	2.036	1.107	1.007	0.738	0.716	50.0	59.4
8.0	4.234	7.296	2.127	1.201	1.027	0.754	0.735	51.0	61.5
10.0	4.218	7.217	2.198	1.308	1.048	0.771	0.756	51.1	63.1
12.0	4.208	7.142	2.250	1.418	1.069	0.789	0.777	50.3	64.1
14.0	4.202	7.073	2.283	1.516	1.091	0.807	0.797	48.9	64.2
16.0	4.200	7.016	2.299	1.589	1.112	0.825	0.817	47.1	63.5
18.0	4.202	6.971	2.298	1.629	1.132	0.843	0.836	45.1	62.1
20.0	4.208	6.940	2.283	1.633	1.152	0.860	0.854	42.9	60.2
22.0	4.217	6.925	2.256	1.606	1.169	0.876	0.870	40.8	58.0
24.0	4.228	6.926	2.219	1.552	1.184	0.891	0.883	38.8	55.7
26.0	4.241	6.942	2.175	1.481	1.197	0.903	0.895	37.1	53.6
28.0	4.255	6.973	2.127	1.399	1.208	0.914	0.904	35.8	51.6
30.0	4.270	7.017	2.079	1.313	1.216	0.923	0.911	34.9	50.0
32.0	4.285	7.074	2.033	1.228	1.222	0.929	0.916	34.4	48.7
34.0	4.300	7.140	1.992	1.148	1.226	0.933	0.919	34.3	47.7
36.0	4.314	7.212	1.957	1.076	1.227	0.936	0.920	34.5	47.1
38.0	4.327	7.287	1.932	1.014	1.226	0.936	0.920	35.0	46.9
40.0	4.338	7.363	1.915	0.962	1.223	0.935	0.918	35.8	47.1
42.0	4.348	7.436	1.907	0.922	1.220	0.933	0.916	36.7	47.6
44.0	4.356	7.504	1.907	0.895	1.215	0.929	0.912	37.7	48.5
46.0	4.362	7.565	1.915	0.880	1.209	0.925	0.908	38.6	49.6
48.0	4.367	7.617	1.928	0.877	1.203	0.920	0.904	39.5	51.0
50.0	4.370	7.659	1.944	0.886	1.196	0.915	0.899	40.3	52.6
52.0	4.372	7.691	1.963	0.907	1.190	0.910	0.894	41.0	54.3
54.0	4.372	7.713	1.983	0.939	1.183	0.904	0.889	41.5	55.9
56.0	4.371	7.725	2.003	0.980	1.177	0.899	0.885	41.9	57.4
58.0	4.369	7.730	2.022	1.029	1.171	0.893	0.880	42.1	58.7
60.0	4.366	7.727	2.039	1.081	1.166	0.888	0.875	42.3	59.7
62.0	4.362	7.718	2.054	1.135	1.161	0.884	0.871	42.2	60.4
64.0	4.358	7.704	2.066	1.187	1.157	0.880	0.868	42.1	60.7
66.0	4.353	7.687	2.076	1.233	1.153	0.877	0.864	41.9	60.6
68.0	4.348	7.666	2.083	1.271	1.150	0.874	0.862	41.7	60.2
70.0	4.343	7.644	2.088	1.298	1.148	0.872	0.860	41.4	59.6
72.0	4.339	7.622	2.091	1.315	1.147	0.870	0.858	41.1	58.8
74.0	4.334	7.599	2.091	1.322	1.146	0.869	0.857	40.8	58.0
76.0	4.330	7.576	2.090	1.321	1.145	0.868	0.856	40.6	57.1
78.0	4.326	7.555	2.088	1.312	1.145	0.868	0.855	40.3	56.2
80.0	4.322	7.536	2.085	1.299	1.146	0.868	0.855	40.1	55.4
82.0	4.319	7.519	2.080	1.282	1.147	0.868	0.856	39.9	54.8
84.0	4.316	7.503	2.076	1.264	1.148	0.869	0.856	39.7	54.3
86.0	4.314	7.491	2.071	1.246	1.149	0.870	0.857	39.6	53.9
88.0	4.312	7.480	2.067	1.228	1.150	0.871	0.858	39.5	53.6
90.0	4.311	7.471	2.062	1.212	1.152	0.872	0.859	39.5	53.5
92.0	4.310	7.465	2.058	1.198	1.154	0.874	0.860	39.4	53.4
94.0	4.309	7.461	2.055	1.186	1.155	0.875	0.861	39.5	53.5
96.0	4.309	7.458	2.052	1.177	1.157	0.876	0.863	39.5	53.6
98.0	4.309	7.457	2.049	1.169	1.158	0.878	0.864	39.5	53.7

TIME	C1	C2	B1	B2	S1	O1	O2	L1	L2
-2.0	4.349	7.507	1.689	0.978	0.952	0.742	0.711	40.0	55.0
-0.0	4.349	7.507	1.689	0.978	0.952	0.742	0.711	40.0	55.0
2.0	4.316	7.489	1.805	0.992	0.969	0.721	0.694	44.2	55.6
4.0	4.283	7.440	1.928	1.036	0.988	0.725	0.700	47.7	57.2
6.0	4.255	7.373	2.036	1.107	1.007	0.738	0.716	50.0	59.4
8.0	4.234	7.296	2.127	1.201	1.027	0.754	0.735	51.0	61.5
10.0	4.218	7.217	2.198	1.308	1.048	0.771	0.756	51.1	63.1
12.0	4.208	7.142	2.250	1.418	1.069	0.789	0.777	50.3	64.1
14.0	4.202	7.073	2.283	1.516	1.091	0.807	0.797	48.9	64.2
16.0	4.200	7.016	2.299	1.589	1.112	0.825	0.817	47.1	63.5
18.0	4.202	6.971	2.298	1.629	1.132	0.843	0.836	45.1	62.1
20.0	4.208	6.940	2.283	1.633	1.152	0.860	0.854	42.9	60.2
22.0	4.217	6.925	2.256	1.606	1.169	0.876	0.870	40.8	58.0
24.0	4.228	6.926	2.219	1.552	1.184	0.891	0.883	38.8	55.7
26.0	4.241	6.942	2.175	1.481	1.197	0.903	0.895	37.1	53.6
28.0	4.255	6.973	2.127	1.399	1.208	0.914	0.904	35.8	51.6
30.0	4.270	7.017	2.079	1.313	1.216	0.923	0.911	34.9	50.0
32.0	4.285	7.074	2.033	1.228	1.222	0.929	0.916	34.4	48.7
34.0	4.300	7.140	1.992	1.148	1.226	0.933	0.919	34.3	47.7
36.0	4.314	7.212	1.957	1.076	1.227	0.936	0.920	34.5	47.1
38.0	4.327	7.287	1.932	1.014	1.226	0.936	0.920	35.0	46.9
40.0	4.338	7.363	1.915	0.962	1.223	0.935	0.918	35.8	47.1
42.0	4.348	7.436	1.907	0.922	1.220	0.933	0.916	36.7	47.6
44.0	4.356	7.504	1.907	0.895	1.215	0.929	0.912	37.7	48.5
46.0	4.362	7.565	1.915	0.880	1.209	0.925	0.908	38.6	49.6
48.0	4.367	7.617	1.928	0.877	1.203	0.920	0.904	39.5	51.0
50.0	4.370	7.659	1.944	0.886	1.196	0.915	0.899	40.3	52.6
52.0	4.372	7.691	1.963	0.907	1.190	0.910	0.894	41.0	54.3
54.0	4.372	7.713	1.983	0.939	1.183	0.904	0.889	41.5	55.9
56.0	4.371	7.725	2.003	0.980	1.177	0.899	0.885	41.9	57.4
58.0	4.369	7.730	2.022	1.029	1.171	0.893	0.880	42.1	58.7
60.0	4.366	7.727	2.039	1.081	1.166	0.888	0.875	42.3	59.7
62.0	4.362	7.718	2.054	1.135	1.161	0.884	0.871	42.2	60.4
64.0	4.358	7.704	2.066	1.187	1.157	0.880	0.868	42.1	60.7
66.0	4.353	7.687	2.076	1.233	1.153	0.877	0.864	41.9	60.6
68.0	4.348	7.666	2.083	1.271	1.150	0.874	0.862	41.7	60.2
70.0	4.343	7.644	2.088	1.298	1.148	0.872	0.860	41.4	59.6
72.0	4.339	7.622	2.091	1.315	1.147	0.870	0.858	41.1	58.8
74.0	4.334	7.599	2.091	1.322	1.146	0.869	0.857	40.8	58.0
76.0	4.330	7.576	2.090	1.321	1.145	0.868	0.856	40.6	57.1
78.0	4.326	7.555	2.088	1.312	1.145	0.868	0.855	40.3	56.2
80.0	4.322	7.536	2.085	1.299	1.146	0.868	0.855	40.1	55.4
82.0	4.319	7.519	2.080	1.282	1.147	0.868	0.856	39.9	54.8
84.0	4.316	7.503	2.076	1.264	1.148	0.869	0.856	39.7	54.3
86.0	4.314	7.491	2.071	1.246	1.149	0.870	0.857	39.6	53.9
88.0	4.312	7.480	2.067	1.228	1.150	0.871	0.858	39.5	53.6
90.0	4.311	7.471	2.062	1.212	1.152	0.872	0.859	39.5	53.5
92.0	4.310	7.465	2.058	1.198	1.154	0.874	0.860	39.4	53.4
94.0	4.309	7.461	2.055	1.186	1.155	0.875	0.861	39.5	53.5
96.0	4.309	7.458	2.052	1.177	1.157	0.876	0.863	39.5	53.6
98.0	4.309	7.457	2.049	1.169	1.158	0.878	0.864	39.5	53.7

..CONTD

TIME	C1	C2	B1	B2	SI	O1	O2	L1	L2
100.0	4.309	7.457	2.047	1.164	1.160	0.879	0.865	39.6	53.9
102.0	4.310	7.458	2.046	1.160	1.161	0.880	0.866	39.6	54.1
104.0	4.311	7.460	2.045	1.158	1.162	0.881	0.867	39.7	54.3
106.0	4.312	7.462	2.044	1.158	1.163	0.882	0.869	39.8	54.5
108.0	4.313	7.465	2.044	1.159	1.164	0.883	0.869	39.8	54.6
110.0	4.314	7.469	2.043	1.160	1.165	0.884	0.870	39.9	54.8
112.0	4.315	7.473	2.043	1.162	1.166	0.884	0.871	39.9	54.9
114.0	4.316	7.477	2.044	1.164	1.166	0.885	0.872	39.9	55.0
116.0	4.317	7.481	2.044	1.166	1.167	0.886	0.872	40.0	55.1
118.0	4.319	7.485	2.044	1.168	1.167	0.886	0.872	40.0	55.1
120.0	4.320	7.490	2.044	1.170	1.167	0.886	0.873	40.0	55.2
122.0	4.321	7.494	2.044	1.171	1.167	0.886	0.873	40.0	55.2
124.0	4.322	7.497	2.045	1.172	1.167	0.886	0.873	40.0	55.2
126.0	4.322	7.501	2.045	1.173	1.167	0.886	0.873	40.0	55.1
128.0	4.323	7.504	2.045	1.174	1.167	0.886	0.873	40.0	55.1
130.0	4.324	7.507	2.045	1.175	1.167	0.886	0.873	40.0	55.1
132.0	4.324	7.510	2.046	1.175	1.166	0.886	0.872	40.0	55.1
134.0	4.325	7.513	2.046	1.175	1.166	0.885	0.872	40.0	55.1
136.0	4.325	7.515	2.046	1.175	1.166	0.885	0.872	40.0	55.1
138.0	4.325	7.516	2.046	1.176	1.165	0.885	0.872	40.0	55.0
140.0	4.325	7.518	2.047	1.176	1.165	0.885	0.871	40.0	55.0
142.0	4.325	7.519	2.047	1.176	1.165	0.884	0.871	40.0	55.0
144.0	4.325	7.519	2.047	1.177	1.164	0.884	0.871	40.0	55.0
146.0	4.325	7.520	2.048	1.177	1.164	0.883	0.870	40.1	55.1
148.0	4.325	7.520	2.048	1.178	1.163	0.883	0.870	40.1	55.1
150.0	4.325	7.519	2.049	1.178	1.163	0.883	0.870	40.1	55.1
152.0	4.324	7.519	2.049	1.179	1.163	0.883	0.869	40.1	55.1
154.0	4.324	7.518	2.049	1.180	1.162	0.882	0.869	40.1	55.1
156.0	4.324	7.517	2.050	1.181	1.162	0.882	0.869	40.1	55.1
158.0	4.324	7.516	2.050	1.181	1.162	0.882	0.869	40.0	55.1
160.0	4.323	7.515	2.050	1.182	1.162	0.882	0.869	40.0	55.1
162.0	4.323	7.514	2.050	1.182	1.162	0.882	0.868	40.0	55.1
164.0	4.323	7.512	2.051	1.183	1.162	0.882	0.868	40.0	55.1
166.0	4.322	7.511	2.051	1.183	1.162	0.882	0.868	40.0	55.1
168.0	4.322	7.510	2.051	1.183	1.162	0.882	0.868	40.0	55.1
170.0	4.322	7.509	2.051	1.184	1.162	0.882	0.868	40.0	55.0
172.0	4.322	7.508	2.051	1.184	1.162	0.882	0.868	40.0	55.0
174.0	4.321	7.507	2.051	1.183	1.162	0.882	0.868	40.0	55.0
176.0	4.321	7.506	2.050	1.183	1.162	0.882	0.868	40.0	55.0
178.0	4.321	7.505	2.050	1.183	1.162	0.882	0.869	40.0	55.0
180.0	4.321	7.504	2.050	1.182	1.162	0.882	0.869	40.0	55.0

CALCULATED FINAL CONDITIONS
F= 2.932, B1= 2.050, B2= 1.182, CF= 0.03021, C1= 0.04321
C2= 0.07504, TF= 90.8, TS1= 210.9, T1= 190.1, SI= 1.162

..CONTD

TIME	C1	C2	B1	B2	S1	O1	O2	L1	L2
100.0	4.309	7.457	2.047	1.164	1.160	0.879	0.865	39.6	53.9
102.0	4.310	7.458	2.046	1.160	1.161	0.880	0.866	39.6	54.1
104.0	4.311	7.460	2.045	1.158	1.162	0.881	0.867	39.7	54.3
106.0	4.312	7.462	2.044	1.158	1.163	0.882	0.869	39.8	54.5
108.0	4.313	7.465	2.044	1.159	1.164	0.883	0.869	39.8	54.6
110.0	4.314	7.469	2.043	1.160	1.165	0.884	0.870	39.9	54.8
112.0	4.315	7.473	2.043	1.162	1.166	0.884	0.871	39.9	54.9
114.0	4.316	7.477	2.044	1.164	1.166	0.885	0.872	39.9	55.0
116.0	4.317	7.481	2.044	1.166	1.167	0.886	0.872	40.0	55.1
118.0	4.319	7.485	2.044	1.168	1.167	0.886	0.872	40.0	55.1
120.0	4.320	7.490	2.044	1.170	1.167	0.886	0.873	40.0	55.2
122.0	4.321	7.494	2.044	1.171	1.167	0.886	0.873	40.0	55.2
124.0	4.322	7.497	2.045	1.172	1.167	0.886	0.873	40.0	55.2
126.0	4.322	7.501	2.045	1.173	1.167	0.886	0.873	40.0	55.1
128.0	4.323	7.504	2.045	1.174	1.167	0.886	0.873	40.0	55.1
130.0	4.324	7.507	2.045	1.175	1.167	0.886	0.873	40.0	55.1
132.0	4.324	7.510	2.046	1.175	1.166	0.886	0.872	40.0	55.1
134.0	4.325	7.513	2.046	1.175	1.166	0.885	0.872	40.0	55.1
136.0	4.325	7.515	2.046	1.175	1.166	0.885	0.872	40.0	55.1
138.0	4.325	7.516	2.046	1.176	1.165	0.885	0.872	40.0	55.0
140.0	4.325	7.518	2.047	1.176	1.165	0.885	0.871	40.0	55.0
142.0	4.325	7.519	2.047	1.176	1.165	0.884	0.871	40.0	55.0
144.0	4.325	7.519	2.047	1.177	1.164	0.884	0.871	40.0	55.0
146.0	4.325	7.520	2.048	1.177	1.164	0.883	0.870	40.1	55.1
148.0	4.325	7.520	2.048	1.178	1.163	0.883	0.870	40.1	55.1
150.0	4.325	7.519	2.049	1.178	1.163	0.883	0.870	40.1	55.1
152.0	4.324	7.519	2.049	1.179	1.163	0.883	0.869	40.1	55.1
154.0	4.324	7.518	2.049	1.180	1.162	0.882	0.869	40.1	55.1
156.0	4.324	7.517	2.050	1.181	1.162	0.882	0.869	40.1	55.1
158.0	4.324	7.516	2.050	1.181	1.162	0.882	0.869	40.0	55.1
160.0	4.323	7.515	2.050	1.182	1.162	0.882	0.869	40.0	55.1
162.0	4.323	7.514	2.050	1.182	1.162	0.882	0.868	40.0	55.1
164.0	4.323	7.512	2.051	1.183	1.162	0.882	0.868	40.0	55.1
166.0	4.322	7.511	2.051	1.183	1.162	0.882	0.868	40.0	55.1
168.0	4.322	7.510	2.051	1.183	1.162	0.882	0.868	40.0	55.1
170.0	4.322	7.509	2.051	1.184	1.162	0.882	0.868	40.0	55.0
172.0	4.322	7.508	2.051	1.184	1.162	0.882	0.868	40.0	55.0
174.0	4.321	7.507	2.051	1.183	1.162	0.882	0.868	40.0	55.0
176.0	4.321	7.506	2.050	1.183	1.162	0.882	0.868	40.0	55.0
178.0	4.321	7.505	2.050	1.183	1.162	0.882	0.869	40.0	55.0
180.0	4.321	7.504	2.050	1.182	1.162	0.882	0.869	40.0	55.0

CALCULATED FINAL CONDITIONS

F= 2.932, B1= 2.050, B2= 1.182, CF= 0.03021, C1= 0.04321

C2= 0.07504, TF= 90.8, TS1= 210.9, T1= 190.1, S1= 1.162

EXPERIMENT 4

CLOSED LOOP RESPONSE TO A STEP UP IN FEED RATE
EFFECT OF INCREASING HL3 BY 25 PERCENT

INPUT DATA

INITIAL CONDITIONS
F= 2.430, B1= 1.690, B2= 0.980, CF= 0.03020, C1= 0.04340
C2= 0.07510, TF= 88.5, TS1= 201.0, T1= 184.0, T2= 149.5
HSI= 1175.1

FINAL CONDITIONS
F= 2.930, B1= 2.050, B2= 1.180, CF= 0.03020, C1= 0.04320
C2= 0.07510, TF= 93.0, TS1= 211.0, T1= 190.0, T2= 149.5
HSI= 1175.1

CALCULATED PARAMETERS
UA1= 55.57, UA2= 20.92, HL2= 13.98, HL3= 55.91

CONTROLLER SETTINGS
KL1= 80.0, KL2= 175.0, KC2= 130.0, TL1= 6.0, TL2= 6.0
TC2= 7.0, TDC2= 5.0

CALCULATED INITIAL CONDITIONS
F= 2.431, B1= 1.684, B2= 0.978, CF= 0.03021, C1= 0.04362
C2= 0.07507, TF= 90.8, TS1= 201.4, T1= 184.1, SI= 0.959

TIME	C1	C2	B1	B2	SI	O1	O2	L1	L2
-2.0	4.362	7.507	1.684	0.978	0.959	0.748	0.705	40.0	55.0
-0.0	4.362	7.507	1.684	0.978	0.959	0.748	0.705	40.0	55.0
2.0	4.329	7.489	1.800	0.992	0.975	0.726	0.688	44.2	55.6
4.0	4.295	7.440	1.923	1.036	0.994	0.730	0.694	47.7	57.3
6.0	4.267	7.373	2.032	1.108	1.013	0.742	0.711	49.9	59.4
8.0	4.246	7.296	2.122	1.202	1.033	0.758	0.730	51.0	61.5
10.0	4.230	7.217	2.194	1.309	1.054	0.775	0.750	51.1	63.2
12.0	4.219	7.141	2.246	1.419	1.075	0.793	0.771	50.3	64.1
14.0	4.213	7.073	2.279	1.517	1.096	0.811	0.792	48.9	64.3
16.0	4.211	7.015	2.294	1.591	1.118	0.830	0.811	47.1	63.6
18.0	4.213	6.970	2.294	1.631	1.138	0.847	0.830	45.0	62.1
20.0	4.218	6.939	2.278	1.635	1.157	0.864	0.848	42.9	60.2
22.0	4.227	6.923	2.251	1.608	1.174	0.880	0.864	40.8	58.0
24.0	4.238	6.924	2.214	1.554	1.190	0.895	0.877	38.8	55.7
26.0	4.251	6.939	2.170	1.483	1.203	0.907	0.889	37.1	53.6
28.0	4.265	6.970	2.123	1.401	1.214	0.918	0.898	35.8	51.6
30.0	4.280	7.014	2.074	1.315	1.222	0.927	0.905	34.9	50.0
32.0	4.295	7.070	2.028	1.230	1.228	0.933	0.910	34.4	48.7
34.0	4.310	7.135	1.987	1.150	1.231	0.938	0.913	34.3	47.7
36.0	4.323	7.207	1.953	1.077	1.233	0.940	0.915	34.5	47.1
38.0	4.336	7.282	1.927	1.015	1.232	0.941	0.915	35.1	46.9
40.0	4.348	7.358	1.910	0.963	1.230	0.940	0.913	35.8	47.1
42.0	4.358	7.431	1.902	0.923	1.226	0.938	0.911	36.7	47.6
44.0	4.366	7.499	1.903	0.896	1.222	0.934	0.907	37.7	48.5
46.0	4.372	7.560	1.910	0.880	1.216	0.930	0.903	38.6	49.6
48.0	4.377	7.612	1.923	0.877	1.210	0.926	0.899	39.5	51.0
50.0	4.380	7.654	1.939	0.887	1.204	0.921	0.895	40.3	52.6
52.0	4.382	7.686	1.958	0.907	1.197	0.915	0.890	41.0	54.2
54.0	4.382	7.709	1.978	0.939	1.191	0.910	0.885	41.5	55.9
56.0	4.382	7.723	1.997	0.979	1.185	0.904	0.880	41.9	57.4
58.0	4.380	7.728	2.016	1.027	1.179	0.899	0.876	42.1	58.7
60.0	4.377	7.726	2.033	1.080	1.173	0.894	0.871	42.2	59.7
62.0	4.373	7.718	2.048	1.133	1.168	0.890	0.867	42.2	60.3
64.0	4.369	7.705	2.060	1.185	1.164	0.886	0.863	42.1	60.6
66.0	4.365	7.688	2.070	1.231	1.161	0.882	0.860	41.9	60.6
68.0	4.360	7.668	2.077	1.268	1.158	0.880	0.857	41.7	60.2
70.0	4.355	7.647	2.082	1.296	1.155	0.877	0.855	41.4	59.6
72.0	4.350	7.624	2.085	1.313	1.154	0.875	0.853	41.1	58.8
74.0	4.346	7.602	2.085	1.320	1.153	0.874	0.852	40.8	58.0
76.0	4.341	7.580	2.084	1.319	1.152	0.873	0.851	40.6	57.1
78.0	4.337	7.559	2.082	1.311	1.152	0.873	0.851	40.3	56.2
80.0	4.334	7.540	2.079	1.298	1.153	0.873	0.850	40.1	55.5
82.0	4.330	7.522	2.075	1.282	1.153	0.873	0.851	39.9	54.8
84.0	4.328	7.507	2.071	1.264	1.154	0.874	0.851	39.7	54.3
86.0	4.325	7.494	2.066	1.246	1.155	0.875	0.852	39.6	53.9
88.0	4.323	7.483	2.062	1.229	1.157	0.876	0.853	39.5	53.7
90.0	4.322	7.474	2.058	1.213	1.158	0.877	0.854	39.5	53.5
92.0	4.321	7.467	2.054	1.199	1.160	0.878	0.855	39.5	53.5
94.0	4.320	7.463	2.050	1.187	1.161	0.880	0.856	39.5	53.5
96.0	4.320	7.459	2.047	1.178	1.163	0.881	0.857	39.5	53.6
98.0	4.320	7.458	2.045	1.171	1.164	0.882	0.859	39.5	53.7

TIME	C1	C2	B1	B2	S1	O1	O2	L1	L2
-2.0	4.362	7.507	1.684	0.978	0.959	0.748	0.705	40.0	55.0
-0.0	4.362	7.507	1.684	0.978	0.959	0.748	0.705	40.0	55.0
2.0	4.329	7.489	1.800	0.992	0.975	0.726	0.688	44.2	55.6
4.0	4.295	7.440	1.923	1.036	0.994	0.730	0.694	47.7	57.3
6.0	4.267	7.373	2.032	1.108	1.013	0.742	0.711	49.9	59.4
8.0	4.246	7.296	2.122	1.202	1.033	0.758	0.730	51.0	61.5
10.0	4.230	7.217	2.194	1.309	1.054	0.775	0.750	51.1	63.2
12.0	4.219	7.141	2.246	1.419	1.075	0.793	0.771	50.3	64.1
14.0	4.213	7.073	2.279	1.517	1.096	0.811	0.792	48.9	64.3
16.0	4.211	7.015	2.294	1.591	1.118	0.830	0.811	47.1	63.6
18.0	4.213	6.970	2.294	1.631	1.138	0.847	0.830	45.0	62.1
20.0	4.218	6.939	2.278	1.635	1.157	0.864	0.848	42.9	60.2
22.0	4.227	6.923	2.251	1.608	1.174	0.880	0.864	40.8	58.0
24.0	4.238	6.924	2.214	1.554	1.190	0.895	0.877	38.8	55.7
26.0	4.251	6.939	2.170	1.483	1.203	0.907	0.889	37.1	53.6
28.0	4.265	6.970	2.123	1.401	1.214	0.918	0.898	35.8	51.6
30.0	4.280	7.014	2.074	1.315	1.222	0.927	0.905	34.9	50.0
32.0	4.295	7.070	2.028	1.230	1.228	0.933	0.910	34.4	48.7
34.0	4.310	7.135	1.987	1.150	1.231	0.938	0.913	34.3	47.7
36.0	4.323	7.207	1.953	1.077	1.233	0.940	0.915	34.5	47.1
38.0	4.336	7.282	1.927	1.015	1.232	0.941	0.915	35.1	46.9
40.0	4.348	7.358	1.910	0.963	1.230	0.940	0.913	35.8	47.1
42.0	4.358	7.431	1.902	0.923	1.226	0.938	0.911	36.7	47.6
44.0	4.366	7.499	1.903	0.896	1.222	0.934	0.907	37.7	48.5
46.0	4.372	7.560	1.910	0.880	1.216	0.930	0.903	38.6	49.6
48.0	4.377	7.612	1.923	0.877	1.210	0.926	0.899	39.5	51.0
50.0	4.380	7.654	1.939	0.887	1.204	0.921	0.895	40.3	52.6
52.0	4.382	7.686	1.958	0.907	1.197	0.915	0.890	41.0	54.2
54.0	4.382	7.709	1.978	0.939	1.191	0.910	0.885	41.5	55.9
56.0	4.382	7.723	1.997	0.979	1.185	0.904	0.880	41.9	57.4
58.0	4.380	7.728	2.016	1.027	1.179	0.899	0.876	42.1	58.7
60.0	4.377	7.726	2.033	1.080	1.173	0.894	0.871	42.2	59.7
62.0	4.373	7.718	2.048	1.133	1.168	0.890	0.867	42.2	60.3
64.0	4.369	7.705	2.060	1.185	1.164	0.886	0.863	42.1	60.6
66.0	4.365	7.688	2.070	1.231	1.161	0.882	0.860	41.9	60.6
68.0	4.360	7.668	2.077	1.268	1.158	0.880	0.857	41.7	60.2
70.0	4.355	7.647	2.082	1.296	1.155	0.877	0.855	41.4	59.6
72.0	4.350	7.624	2.085	1.313	1.154	0.875	0.853	41.1	58.8
74.0	4.346	7.602	2.085	1.320	1.153	0.874	0.852	40.8	58.0
76.0	4.341	7.580	2.084	1.319	1.152	0.873	0.851	40.6	57.1
78.0	4.337	7.559	2.082	1.311	1.152	0.873	0.851	40.3	56.2
80.0	4.334	7.540	2.079	1.298	1.153	0.873	0.850	40.1	55.5
82.0	4.330	7.522	2.075	1.282	1.153	0.873	0.851	39.9	54.8
84.0	4.328	7.507	2.071	1.264	1.154	0.874	0.851	39.7	54.3
86.0	4.325	7.494	2.066	1.246	1.155	0.875	0.852	39.6	53.9
88.0	4.323	7.483	2.062	1.229	1.157	0.876	0.853	39.5	53.7
90.0	4.322	7.474	2.058	1.213	1.158	0.877	0.854	39.5	53.5
92.0	4.321	7.467	2.054	1.199	1.160	0.878	0.855	39.5	53.5
94.0	4.320	7.463	2.050	1.187	1.161	0.880	0.856	39.5	53.5
96.0	4.320	7.459	2.047	1.178	1.163	0.881	0.857	39.5	53.6
98.0	4.320	7.458	2.045	1.171	1.164	0.882	0.859	39.5	53.7

..CONTD

TIME	C1	C2	B1	B2	SI	O1	O2	L1	L2
100.0	4.320	7.457	2.043	1.165	1.166	0.884	0.860	39.6	53.9
102.0	4.321	7.458	2.042	1.162	1.167	0.885	0.861	39.6	54.1
104.0	4.321	7.459	2.040	1.160	1.168	0.886	0.862	39.7	54.3
106.0	4.322	7.462	2.040	1.159	1.169	0.887	0.863	39.8	54.5
108.0	4.323	7.465	2.039	1.160	1.170	0.888	0.864	39.8	54.6
110.0	4.324	7.468	2.039	1.161	1.171	0.889	0.865	39.8	54.8
112.0	4.325	7.472	2.039	1.163	1.172	0.889	0.866	39.9	54.9
114.0	4.327	7.476	2.039	1.165	1.173	0.890	0.866	39.9	55.0
116.0	4.328	7.480	2.039	1.166	1.173	0.890	0.867	39.9	55.1
118.0	4.329	7.484	2.039	1.168	1.174	0.891	0.867	40.0	55.1
120.0	4.330	7.488	2.039	1.170	1.174	0.891	0.868	40.0	55.1
122.0	4.331	7.492	2.039	1.171	1.174	0.891	0.868	40.0	55.1
124.0	4.332	7.496	2.039	1.172	1.174	0.891	0.868	40.0	55.1
126.0	4.333	7.500	2.040	1.173	1.174	0.891	0.868	40.0	55.1
128.0	4.334	7.503	2.040	1.174	1.174	0.891	0.868	40.0	55.1
130.0	4.334	7.506	2.040	1.174	1.173	0.891	0.868	40.0	55.1
132.0	4.335	7.509	2.040	1.174	1.173	0.891	0.867	40.0	55.1
134.0	4.335	7.512	2.041	1.175	1.173	0.891	0.867	40.0	55.1
136.0	4.336	7.514	2.041	1.175	1.172	0.890	0.867	40.0	55.0
138.0	4.336	7.516	2.041	1.175	1.172	0.890	0.867	40.0	55.0
140.0	4.336	7.517	2.041	1.175	1.172	0.890	0.866	40.0	55.0
142.0	4.336	7.518	2.042	1.176	1.171	0.889	0.866	40.0	55.0
144.0	4.336	7.519	2.042	1.176	1.171	0.889	0.866	40.0	55.0
146.0	4.336	7.520	2.043	1.177	1.170	0.889	0.865	40.1	55.1
148.0	4.336	7.520	2.043	1.177	1.170	0.888	0.865	40.1	55.1
150.0	4.336	7.520	2.043	1.178	1.170	0.888	0.865	40.1	55.1
152.0	4.335	7.519	2.044	1.179	1.169	0.888	0.864	40.1	55.1
154.0	4.335	7.518	2.044	1.180	1.169	0.888	0.864	40.1	55.1
156.0	4.335	7.518	2.045	1.180	1.169	0.887	0.864	40.1	55.1
158.0	4.334	7.517	2.045	1.181	1.169	0.887	0.864	40.1	55.1
160.0	4.334	7.515	2.045	1.182	1.169	0.887	0.864	40.0	55.1
162.0	4.334	7.514	2.045	1.182	1.168	0.887	0.863	40.0	55.1
164.0	4.333	7.513	2.045	1.183	1.168	0.887	0.863	40.0	55.1
166.0	4.333	7.512	2.046	1.183	1.168	0.887	0.863	40.0	55.1
168.0	4.333	7.510	2.046	1.184	1.168	0.887	0.863	40.0	55.1
170.0	4.333	7.509	2.046	1.184	1.168	0.887	0.863	40.0	55.0
172.0	4.332	7.508	2.046	1.184	1.168	0.887	0.863	40.0	55.0
174.0	4.332	7.507	2.045	1.183	1.168	0.887	0.863	40.0	55.0
176.0	4.332	7.506	2.045	1.183	1.169	0.887	0.863	40.0	55.0
178.0	4.332	7.505	2.045	1.183	1.169	0.887	0.863	40.0	55.0
180.0	4.332	7.505	2.045	1.183	1.169	0.887	0.863	40.0	55.0

CALCULATED FINAL CONDITIONS
F= 2.932, B1= 2.045, B2= 1.183, CF= 0.03021, C1= 0.04332
C2= 0.07505, TF= 90.8, TS1= 211.4, T1= 190.5, SI= 1.169

..CONTD

TIME	C1	C2	B1	B2	S1	O1	O2	L1	L2
100.0	4.320	7.457	2.043	1.165	1.166	0.884	0.860	39.6	53.9
102.0	4.321	7.458	2.042	1.162	1.167	0.885	0.861	39.6	54.1
104.0	4.321	7.459	2.040	1.160	1.168	0.886	0.862	39.7	54.3
106.0	4.322	7.462	2.040	1.159	1.169	0.887	0.863	39.8	54.5
108.0	4.323	7.465	2.039	1.160	1.170	0.888	0.864	39.8	54.6
110.0	4.324	7.468	2.039	1.161	1.171	0.889	0.865	39.8	54.8
112.0	4.325	7.472	2.039	1.163	1.172	0.889	0.866	39.9	54.9
114.0	4.327	7.476	2.039	1.165	1.173	0.890	0.866	39.9	55.0
116.0	4.328	7.480	2.039	1.166	1.173	0.890	0.867	39.9	55.1
118.0	4.329	7.484	2.039	1.168	1.174	0.891	0.867	40.0	55.1
120.0	4.330	7.488	2.039	1.170	1.174	0.891	0.868	40.0	55.1
122.0	4.331	7.492	2.039	1.171	1.174	0.891	0.868	40.0	55.1
124.0	4.332	7.496	2.039	1.172	1.174	0.891	0.868	40.0	55.1
126.0	4.333	7.500	2.040	1.173	1.174	0.891	0.868	40.0	55.1
128.0	4.334	7.503	2.040	1.174	1.174	0.891	0.868	40.0	55.1
130.0	4.334	7.506	2.040	1.174	1.173	0.891	0.868	40.0	55.1
132.0	4.335	7.509	2.040	1.174	1.173	0.891	0.867	40.0	55.1
134.0	4.335	7.512	2.041	1.175	1.173	0.891	0.867	40.0	55.1
136.0	4.336	7.514	2.041	1.175	1.172	0.890	0.867	40.0	55.0
138.0	4.336	7.516	2.041	1.175	1.172	0.890	0.867	40.0	55.0
140.0	4.336	7.517	2.041	1.175	1.172	0.890	0.866	40.0	55.0
142.0	4.336	7.518	2.042	1.176	1.171	0.889	0.866	40.0	55.0
144.0	4.336	7.519	2.042	1.176	1.171	0.889	0.866	40.0	55.0
146.0	4.336	7.520	2.043	1.177	1.170	0.889	0.865	40.1	55.1
148.0	4.336	7.520	2.043	1.177	1.170	0.888	0.865	40.1	55.1
150.0	4.336	7.520	2.043	1.178	1.170	0.888	0.865	40.1	55.1
152.0	4.335	7.519	2.044	1.179	1.169	0.888	0.864	40.1	55.1
154.0	4.335	7.518	2.044	1.180	1.169	0.888	0.864	40.1	55.1
156.0	4.335	7.518	2.045	1.180	1.169	0.887	0.864	40.1	55.1
158.0	4.334	7.517	2.045	1.181	1.169	0.887	0.864	40.1	55.1
160.0	4.334	7.515	2.045	1.182	1.169	0.887	0.864	40.0	55.1
162.0	4.334	7.514	2.045	1.182	1.168	0.887	0.863	40.0	55.1
164.0	4.333	7.513	2.045	1.183	1.168	0.887	0.863	40.0	55.1
166.0	4.333	7.512	2.046	1.183	1.168	0.887	0.863	40.0	55.1
168.0	4.333	7.510	2.046	1.184	1.168	0.887	0.863	40.0	55.1
170.0	4.333	7.509	2.046	1.184	1.168	0.887	0.863	40.0	55.0
172.0	4.332	7.508	2.046	1.184	1.168	0.887	0.863	40.0	55.0
174.0	4.332	7.507	2.045	1.183	1.168	0.887	0.863	40.0	55.0
176.0	4.332	7.506	2.045	1.183	1.169	0.887	0.863	40.0	55.0
178.0	4.332	7.505	2.045	1.183	1.169	0.887	0.863	40.0	55.0
180.0	4.332	7.505	2.045	1.183	1.169	0.887	0.863	40.0	55.0

CALCULATED FINAL CONDITIONS

F= 2.932, B1= 2.045, B2= 1.183, CF= 0.03021, C1= 0.04332

C2= 0.07505, TF= 90.8, TS1= 211.4, T1= 190.5, S1= 1.169

APPENDIX 10

LINEAR MODEL AND RESULTS

The linear model was derived by linearization of the original model's equations in the manner shown in Chapter II. Since this model was solved in precisely the same manner as the non-linear model only the sub-routine that calculates the coefficients of the linear equations is included in this appendix.

For programming convenience, each of the parameters of the system were given numbers which are

No.	
1	first effect holdup, W_1
2	first effect enthalpy, H_1
3	first effect concentration, C_1
4	second effect holdup, W_2
5	second effect concentration, C_2
6	first effect product, B_1
7	second effect product, B_2
8	steam rate, Si
9	feed rate, F
10	feed enthalpy, Hf
11	feed concentration, Cf
12	second effect temperatures, T_2

In the program, for example, the symbol 02(5) is equal to

$$\frac{\partial O_2}{\partial C_2} = 02(5)$$

The results given in this appendix include the transient data for experiment 4 plus the normalized linear differential equations of the model and the normalized linear control equations. The parameters of these linear equations are actually deviation variables and are not equal to the other parameters of these results though the nomenclature is the same.

```
      SUBROUTINE MATRI(Y,B10,B20,SI,HF,CF,T2,UA1,UA2,F,HSI,A,V)
C     THIS SUBROUTINE CALCULATES THE MATRIX OF THE LINEAR MODEL
      DIMENSION H2(12),T1(3),TS1(8),Q1(8),Q2(12),O1(12),O2(12)
      DIMENSION A(8,12),Y(12),V(12),R(8,12)
      DO 10 I=1,5
      DO 10 J=1,12
10    A(I,J)=0.0
      W1R=Y(2)
      H1=Y(3)/W1R
      C1=Y(4)/W1R
      W2R=Y(5)
      C2=Y(6)/W2R
      T1B=(H1+32.1-6.*C1)/(1.-.454*C1)
      TS1B=(SI*(HSI+32.)+T1B*UA1)/(UA1+SI)
      H2B=T2*(1.-.454*C2)-32.1+6.*C2
      HVAP=1098.-.6*T1B
      O1B=F-B10
      O2B=B10-B20
      HO2=1066.1+.4*T2
      HO1=1066.1+.4*T1B
      H2(5)=6.0-.454*T2
      H2(12)=1.-.454*C2
      T1(2)=1./(1.-.454*C1)
      T1(3)=(.454*T1B-6.0)/(1.-.454*C1)
      TS1(2)=UA1*T1(2)/(UA1+SI)
      TS1(3)=UA1*T1(3)/(UA1+SI)
      TS1(8)=(HSI+32.-TS1B)/(UA1+SI)
      Q1(2)=UA1*(TS1(2)-T1(2))
      Q1(3)=UA1*(TS1(3)-T1(3))
      Q1(8)=UA1*TS1(8)
      Q2(2)=UA2*T1(2)
      Q2(3)=UA2*T1(3)
      Q2(12)=-UA2
      O1(2)=(Q2(2)+.6*O1B*T1(2))/HVAP
      O1(3)=(Q2(3)+.6*O1B*T1(3))/HVAP
      O1(12)=Q2(12)/HVAP
      Z=6.-.454*T2
      DEN=HO2-H2B+Z*C2
      O2(2)=(Q2(2)+B10)/DEN
      O2(3)=(Q2(3)-Z*B10)/DEN
      O2(5)=(B20*Z-B10*H2(5))/DEN
      O2(6)=(H1-H2B+Z*(C2-C1))/DEN
      O2(12)=(Q2(12)-O2B*.4-B20*H2(12))/DEN
      A(1,2)=-O1(2)
      A(1,3)=-O1(3)
      A(1,6)=-1.0
      A(1,9)=1.0
      A(1,12)=-O1(12)
      A(2,2)=(F-O1B-O1B*.4*T1(2)-(HO1-H1)*O1(2)+Q1(2))/W1R
      A(2,3)=(-O1B*.4*T1(3)-(HO1-H1)*O1(3)+Q1(3))/W1R
      A(2,8)=Q1(8)/W1R
      A(2,9)=(HF-H1)/W1R
```

```
      SUBROUTINE MATRIX(Y,B10,B20,S1,HF,CF,T2,UA1,UA2,F,HS1,A,V)
C     THIS SUBROUTINE CALCULATES THE MATRIX OF THE LINEAR MODEL
      DIMENSION H2(12),T1(3),TS1(8),Q1(8),Q2(12),O1(12),O2(12)
      DIMENSION A(8,12),Y(12),V(12),R(8,12)
      DO 10 I=1,5
      DO 10 J=1,12
   10 A(I,J)=0.0
      W1R=Y(2)
      H1=Y(3)/W1R
      C1=Y(4)/W1R
      W2R=Y(5)
      C2=Y(6)/W2R
      T1B=(H1+32.1-6.*C1)/(1.-.454*C1)
      TS1B=(S1*(HS1+32.)+T1B*UA1)/(UA1+S1)
      H2B=T2*(1.-.454*C2)-32.1+6.*C2
      HVAP=1098.-.6*T1B
      O1B=F-B10
      O2B=B10-B20
      HO2=1066.1+.4*T2
      HO1=1066.1+.4*T1B
      H2(5)=6.0-.454*T2
      H2(12)=1.-.454*C2
      T1(2)=1./(1.-.454*C1)
      T1(3)=(.454*T1B-6.0)/(1.-.454*C1)
      TS1(2)=UA1*T1(2)/(UA1+S1)
      TS1(3)=UA1*T1(3)/(UA1+S1)
      TS1(8)=(HS1+32.-TS1B)/(UA1+S1)
      Q1(2)=UA1*(TS1(2)-T1(2))
      Q1(3)=UA1*(TS1(3)-T1(3))
      Q1(8)=UA1*TS1(8)
      Q2(2)=UA2*T1(2)
      Q2(3)=UA2*T1(3)
      Q2(12)=-UA2
      O1(2)=(Q2(2)+.6*O1B*T1(2))/HVAP
      O1(3)=(Q2(3)+.6*O1B*T1(3))/HVAP
      O1(12)=Q2(12)/HVAP
      Z=6.-.454*T2
      DEN=HO2-H2B+Z*C2
      O2(2)=(Q2(2)+B10)/DEN
      O2(3)=(Q2(3)-Z*B10)/DEN
      O2(5)=(B20*Z-B10*H2(5))/DEN
      O2(6)=(H1-H2B+Z*(C2-C1))/DEN
      O2(12)=(Q2(12)-O2B*.4-B20*H2(12))/DEN
      A(1,2)=-O1(2)
      A(1,3)=-O1(3)
      A(1,6)=-1.0
      A(1,9)=1.0
      A(1,12)=-O1(12)
      A(2,2)=(F-O1B-O1B*.4*T1(2)-(HO1-H1)*O1(2)+Q1(2))/W1R
      A(2,3)=(-O1B*.4*T1(3)-(HO1-H1)*O1(3)+Q1(3))/W1R
      A(2,8)=Q1(8)/W1R
      A(2,9)=(HF-H1)/W1R
```

```
      A(2,10)=F/W1R
      A(2,12)=(H01-H1)*01(12)/W1R
      A(3,2)=C1*01(2)/W1R
      A(3,3)=(C1*01(3)-B10)/W1R
      A(3,9)=(CF-C1)/W1R
      A(3,11)=F/W1R
      A(3,12)=C1*01(12)/W1R
      A(4,2)=-02(2)
      A(4,3)=-02(3)
      A(4,5)=-02(5)
      A(4,6)=1.-02(6)
      A(4,7)=-1.
      A(4,12)=-02(12)
      A(5,2)=C2*02(2)/W2R
      A(5,3)=(B10+C2*02(3))/W2R
      A(5,5)=(-B20+C2*02(5))/W2R
      A(5,6)=(C1-C2+02(6)*C2)/W2R
      A(5,12)=C2*02(12)/W2R
      V(1)=W1R
      V(2)=H1
      V(3)=C1
      V(4)=W2R
      V(5)=C2
      V(6)=B10
      V(7)=B20
      V(8)=SI
      V(9)=F
      V(10)=HF
      V(11)=CF
      V(12)=T2
      DO 11 I=1,5
      DO 11 J=1,12
 11   R(I,J)=A(I,J)*V(J)/V(I)
      WRITE(6,16)
      WRITE(6,15) R(1,2),R(1,3),R(1,6),R(1,9),R(1,12)
      WRITE(6,17) R(2,2),R(2,3),R(2,8),R(2,9),R(2,10),R(2,12)
      WRITE(6,18) R(3,2),R(3,3),R(3,9),R(3,11),R(3,12)
      WRITE(6,19) R(4,2),R(4,3),R(4,5),R(4,6),R(4,7),R(4,12)
      WRITE(6,20)  R(5,2),R(5,3),R(5,5),R(5,6),R(5,12)
      RETURN
 15   FORMAT(1HJ,14X,7HDW1/DT=,E10.3,3HH1,,E10.3,3HC1,,E10.3,3HB1,/22X,E
     110.3,2HF,,E10.3,2HT2)
 17   FORMAT(1HJ,14X,7HDH1/DT=,E10.3,3HH1,,E10.3,3HC1,,E10.3,3HSI,/22X,E
     110.3,2HF,,E10.3,3HHF,,E10.3,2HT2)
 18   FORMAT(1HJ,14X,7HDC1/DT=,E10.3,3HH1,,E10.3,3HC1,,E10.3,2HF,/22X,E1
     10.3,3HCF,,E10.3,2HT2)
 19   FORMAT(1HJ,14X,7HDW2/DT=,E10.3,3HH1,,E10.3,3HC1,,E10.3,3HC2,/22X,E
     110.3,3HB1,,E10.3,3HB2,,E10.3,2HT2)
 20   FORMAT(1HJ,14X,7HDC2/DT=,E10.3,3HH1,,E10.3,3HC1,,E10.3,3HC2,/22X,E
     110.3,3HB1,,E10.3,2HT2)
 16   FORMAT(1HK,14X,27HNORMALIZED LINEAR EQUATIONS)
      END
```

```
      A(2,10)=F/W1R
      A(2,12)=(HO1-H1)*O1(12)/W1R
      A(3,2)=C1*O1(2)/W1R
      A(3,3)=(C1*O1(3)-B10)/W1R
      A(3,9)=(CF-C1)/W1R
      A(3,11)=F/W1R
      A(3,12)=C1*O1(12)/W1R
      A(4,2)=-O2(2)
      A(4,3)=-O2(3)
      A(4,5)=-O2(5)
      A(4,6)=1.-O2(6)
      A(4,7)=-1.
      A(4,12)=-O2(12)
      A(5,2)=C2*O2(2)/W2R
      A(5,3)=(B10+C2*O2(3))/W2R
      A(5,5)=(-B20+C2*O2(5))/W2R
      A(5,6)=(C1-C2+O2(6)*C2)/W2R
      A(5,12)=C2*O2(12)/W2R
      V(1)=W1R
      V(2)=H1
      V(3)=C1
      V(4)=W2R
      V(5)=C2
      V(6)=B10
      V(7)=B20
      V(8)=S1
      V(9)=F
      V(10)=HF
      V(11)=CF
      V(12)=T2
      DO 11 I=1,5
      DO 11 J=1,12
   11 R(I,J)=A(I,J)*V(J)/V(I)
      WRITE(6,16)
      WRITE(6,15) R(1,2),R(1,3),R(1,6),R(1,9),R(1,12)
      WRITE(6,17) R(2,2),R(2,3),R(2,8),R(2,9),R(2,10),R(2,12)
      WRITE(6,18) R(3,2),R(3,3),R(3,9),R(3,11),R(3,12)
      WRITE(6,19) R(4,2),R(4,3),R(4,5),R(4,6),R(4,7),R(4,12)
      WRITE(6,20) R(5,2),R(5,3),R(5,5),R(5,6),R(5,12)
      RETURN
   15 FORMAT(1HJ,14X,7HDW1/DT=,E10.3,3HH1,,E10.3,3HC1,,E10.3,3HB1,/22X,E
     110.3,2HF,,E10.3,2HT2)
   17 FORMAT(1HJ,14X,7HDH1/DT=,E10.3,3HH1,,E10.3,3HC1,,E10.3,3HS1,/22X,E
     110.3,2HF,,E10.3,3HHF,,E10.3,2HT2)
   18 FORMAT(1HJ,14X,7HDC1/DT=,E10.3,3HH1,,E10.3,3HC1,,E10.3,2HF,/22X,E1
     10.3,3HCF,,E10.3,2HT2)
   19 FORMAT(1HJ,14X,7HDW2/DT=,E10.3,3HH1,,E10.3,3HC1,,E10.3,3HC2,/22X,E
     110.3,3HB1,,E10.3,3HB2,,E10.3,2HT2)
   20 FORMAT(1HJ,14X,7HDC2/DT=,E10.3,3HH1,,E10.3,3HC1,,E10.3,3HC2,/22X,E
     110.3,3HB1,,E10.3,2HT2)
   16 FORMAT(1HK,14X,27HNORMALIZED LINEAR EQUATIONS)
      END
```

EXPERIMENT 4

CLOSED LOOP RESPONSE TO A STEP UP IN FEED RATE
SOLUTION TO THE LINEARIZED MODEL

INPUT DATA

INITIAL CONDITIONS
F= 2.430, B1= 1.690, B2= 0.980, CF= 0.03020, C1= 0.04340
C2= 0.07510, TF= 88.5, TS1= 201.0, T1= 184.0, T2= 149.5
HsI= 1175.1

FINAL CONDITIONS
F= 2.930, B1= 2.050, B2= 1.180, CF= 0.03020, Ci= 0.04320
C2= 0.07510, TF= 93.0, TS1= 211.0, T1= 190.0, T2= 149.5
Hsi= 1175.1

CALCULATED PARAMETERS
UA1= 55.57, UA2= 20.92, HL2= 13.98, HL3= 55.91

CONTROLLER SETTINGS
KL1= 80.0, KL2= 175.0, KC2= 130.0, TL1= 6.0, TL2= 6.0
TC2= 7.0, TDC2= 5.0

CALCULATED INITIAL CONDTIONS
F= 2.431, B1= 1.691, B2= 0.978, CF= 0.03021, C1= 0.04344
C2= 0.07507, TF= 90.8, TS1= 201.0, T1= 183.8, SI= 0.951

NORMALIZED LINEAR EQUATIONS

DW1/DT=-0.871E-01H1,-0.198E-02C1,-0.450E-01B1,
0.647E-01F, 0.843E-01T2

DH1/DT=-0.571E 00H1,-0.140E-01C1, 0.169E 00SI,
-0.396E-01F, 0.251E-01Hf,-0.563E 00T2

DC1/DT= 0.871E-01H1,-0.430E-01C1,-0.197E-01F,
0.450E-01CF,-0.843E-01T2

DW2/DT=-0.126E 00H1,-0.282E-02C1,-0.122E-03C2,
0.609E-01B1,-0.364E-01B2, 0.122E 00T2

CD2/Dt= 0.126E 00H1, 0.393E-01C1,-0.363E-01C2,
-0.244E-01B1,-0.122E 00T2

B1= 0.281E 01W1 + 0.469E 00INT(W1)

B2= 0.139E 01W2 + 0.232E 00INT(W2)

SI=-0.124E 01C2 -0.177E 00INT(C2)-0.620E 01DC2/DT

TIME	C1	C2	B1	B2	SI
-2.0	4.344	7.507	1.691	0.978	0.951
-0.0	4.344	7.507	1.691	0.978	0.951
2.0	4.310	7.486	1.811	0.985	0.970
4.0	4.275	7.430	1.945	1.009	0.992
6.0	4.245	7.354	2.066	1.049	1.015
8.0	4.222	7.268	2.164	1.102	1.039
10.0	4.207	7.181	2.236	1.166	1.064
12.0	4.198	7.101	2.279	1.236	1.090
14.0	4.196	7.033	2.295	1.306	1.114
16.0	4.199	6.984	2.287	1.373	1.136
18.0	4.207	6.956	2.259	1.431	1.156
20.0	4.219	6.950	2.218	1.476	1.173
22.0	4.235	6.966	2.167	1.506	1.187
24.0	4.252	7.002	2.113	1.518	1.197
26.0	4.270	7.056	2.059	1.512	1.204
28.0	4.289	7.124	2.011	1.489	1.207
30.0	4.307	7.201	1.970	1.450	1.208
32.0	4.324	7.284	1.938	1.397	1.205
34.0	4.339	7.367	1.917	1.335	1.201
36.0	4.352	7.448	1.906	1.266	1.194
38.0	4.362	7.523	1.904	1.194	1.186
40.0	4.370	7.588	1.911	1.124	1.178
42.0	4.376	7.643	1.925	1.058	1.169
44.0	4.379	7.686	1.944	0.999	1.159
46.0	4.379	7.717	1.966	0.950	1.151
48.0	4.378	7.736	1.990	0.913	1.142
50.0	4.375	7.744	2.013	0.889	1.135
52.0	4.370	7.741	2.036	0.878	1.129
54.0	4.365	7.730	2.056	0.880	1.123
56.0	4.358	7.711	2.072	0.894	1.119
58.0	4.351	7.687	2.086	0.918	1.116
60.0	4.344	7.660	2.096	0.952	1.114
62.0	4.337	7.631	2.102	0.993	1.113
64.0	4.330	7.600	2.105	1.039	1.113
66.0	4.324	7.571	2.105	1.088	1.113
68.0	4.318	7.544	2.102	1.137	1.114
70.0	4.313	7.518	2.098	1.185	1.116
72.0	4.309	7.497	2.092	1.229	1.118
74.0	4.305	7.478	2.086	1.269	1.121
76.0	4.303	7.463	2.079	1.303	1.123
78.0	4.301	7.452	2.072	1.330	1.126
80.0	4.300	7.444	2.065	1.350	1.128
82.0	4.299	7.440	2.059	1.362	1.131
84.0	4.299	4.438	2.053	1.367	1.133
86.0	4.300	7.439	2.048	1.365	1.135
88.0	4.301	7.443	2.044	1.357	1.137
90.0	4.302	7.447	2.042	1.343	1.138
92.0	4.304	7.453	2.039	1.325	1.139
94.0	4.305	7.460	2.038	1.303	1.140
96.0	4.307	7.468	2.037	1.378	1.141
98.0	4.309	7.475	2.037	1.252	1.141

..CONTD

TIME	C1	C2	B1	B2	SI
100.0	4.311	7.483	2.037	1.226	1.141
102.0	4.312	7.490	2.038	1.200	1.141
104.0	4.314	7.497	2.039	1.175	1.141
106.0	4.315	7.503	2.040	1.153	1.141
108.0	4.317	7.508	2.042	1.133	1.140
110.0	4.317	7.513	2.043	1.116	1.139
112.0	4.318	7.517	2.044	1.103	1.139
114.0	4.319	7.520	2.045	1.094	1.138
116.0	4.319	7.522	2.047	1.087	1.137
118.0	4.319	7.523	2.048	1.085	1.137
120.0	4.319	7.524	2.049	1.086	1.136
122.0	4.319	7.524	2.050	1.090	1.136
124.0	4.319	7.524	2.051	1.096	1.135
126.0	4.319	7.523	2.051	1.105	1.135
128.0	4.318	7.522	2.052	1.115	1.134
130.0	4.318	7.520	2.052	1.126	1.134
132.0	4.317	7.519	2.053	1.139	1.134
134.0	4.317	7.517	2.053	1.151	1.134
136.0	4.316	7.515	2.053	1.164	1.134
138.0	4.316	7.513	2.053	1.176	1.133
140.0	4.315	7.511	2.053	1.187	1.134
142.0	4.315	7.509	2.053	1.197	1.134
144.0	4.314	7.507	2.052	1.205	1.134
146.0	4.314	7.506	2.052	1.212	1.134
148.0	4.314	7.505	2.052	1.128	1.134
150.0	4.314	7.504	2.052	1.221	1.134
152.0	4.313	7.503	2.051	1.223	1.135
154.0	4.313	7.502	2.051	1.224	1.135
156.0	4.313	7.502	2.051	1.223	1.135
158.0	4.313	7.502	2.050	1.220	1.135
160.0	4.313	7.502	2.050	1.217	1.135
162.0	4.314	7.502	2.050	1.213	1.135
164.0	4.314	7.502	2.050	1.208	1.135
166.0	4.314	7.503	2.049	1.202	1.136
168.0	4.314	7.503	2.049	1.197	1.136
170.0	4.314	7.504	2.049	1.191	1.136
172.0	4.314	7.504	2.049	1.185	1.136
174.0	4.314	7.505	2.049	1.180	1.136
176.0	4.314	7.505	2.049	1.175	1.136
178.0	4.315	7.506	2.049	1.171	1.136
180.0	4.315	7.506	2.049	1.167	1.136
182.0	4.315	7.507	2.049	1.164	1.136

CALCULATED FINAL CONDITIONS
F= 2.932, B1= 2.049, B2= 1.164, CF= 0.03021, C1= 0.04315
C2= 0.07507, TF= 90.8, TS1= 210.7, T1= 190.3, SI= 1.136

APPENDIX 11

MIMIC PROGRAM FOR SOLVING THE MODEL

As can be seen, the coding for the solution of this model via MIMIC is very similar to Fortran programming. However, MIMIC also has the proviso that coding can be of a form more familiar to analog users, if this be so desired. For example,

$$A = C \times D$$

can be coded as

```
A     C*D
```

or

```
A     MDY(C,D)
```

with similar functions for the other arithmetic operations.

The results produced by this MIMIC program were very similar to those produced by the Fortran solution to the model. Unfortunately the user does not have enough control over the output format to allow the output to be put in a form that could be presented here and therefore the results have been omitted. As mentioned in Chapter VII, MIMIC required roughly 7 times as much computer time as did the Fortran program to solve the model and further that MIMIC requires that initial conditions be calculated prior to the use of MIMIC. It is felt these drawbacks of MIMIC over-weigh the virtue of being very simple to use and for that reason MIMIC was not used for this work.

```
*********MIMIC SOURCE************
          CON(W1R,Y20,Y30,W2R,Y50,C2R)
          CON(HF,UA1,UA2,HL2,HL3,KL1)
          CON(KL2,KC2,TL1,TL2,TC2,TDC2)
          CON(B10,B20,SI0,F0,F1,SDENS)
          CON(DHDC,DT,T2,CF,DTMIN,HSI)
 SINOR    SI0/(0.68*SDENS)
 SIGSI0   EXP(2.1978,SINOR)
 F        FSW(T-4.,F0,F1,F1)
 EW1      (Y1-W1R)*20.5
 EW2      (Y4-W2R)*20.5
 EC2      (C2R-C2)*125000.
 C1       Y3/Y1
 H1       Y2/Y1
 C2       Y5/Y4
 SIGL1    (EW1+Y6)/KL1+SIGL10
 DELV     3.9413*(EW2+Y7)/KL2
 B1       1.33*EXP(.481,SIGL1)
 B2       B20*EXP(DELV,10.)
 T1       (H1+32.1-6.*C1)/(1.-.454*C1)
 H2       T2*(1.-.454*C2)-32.1+6.*C2
 Q2       UA2*(T1-T2)
 H02      1066.1+.4*T2
 HVAP     1098.-.6*T1
 H01      1068.73+.386*T1
 NUM      Q2-HL3+B1*(H1-H2-DHDC*(C1-C2))
 DEN      DHDC*C2+H02-H2
 O2       NUM/DEN
 O1       (Q2+HL2)/HVAP
 FDERC2   100.*(B1*(C2-C1)-O2*C2)/(.0008*Y4)
 SIGSI    (EC2+Y8+TDC2*FDERC2)/KC2+SIGSI0
 SI       0.68*SDENS*EXP(.455,SIGSI)
 TS1      (SI*(HSI+32.)+T1*UA1)/(UA1+SI)
 Q1       UA1*(TS1-T1)
 B1NOR    B10/1.33
 SIGL10   EXP(2.079,B1NOR)
 Y1       INT(F-B1-O1,W1R)
 Y2       INT(F*HF+Q1-B1*H1-O1*H01,Y20)
 Y3       INT(F*CF-B1*C1,Y30)
 Y4       INT(B1-B2-O2,W2R)
 Y5       INT(B1*C1-B2*C2,Y50)
 Y6       INT(EW1/TL1,0.0)
 Y7       INT(EW2/TL2,0.0)
 Y8       INT(EC2/TC2,0.0)
 TIME     T-4.0
          FIN(T,184.)
          HDR(T,C1,C2,B1,B2,SI)
          HDR
          OUT(TIME,C1,C2,B1,B2,SI)
          END
END
```

```
*********MIMIC SOURCE************
        CON(W1R,Y20,Y30,W2R,Y50,C2R)
        CON(HF,UA1,UA2,HL2,HL3,KL1)
        CON(KL2,KC2,TL1,TL2,TC2,TDC2)
        CON(B10,B20,SI0,F0,F1,SDENS)
        CON(DHDC,DT,T2,CF,DTMIN,HSI)
SINOR   SI0/(0.68*SDENS)
SIGSI0  EXP(2.1978,SINOR)
F       FSW(T-4.,F0,F1,F1)
EW1     (Y1-W1R)*20.5
EW2     (Y4-W2R)*20.5
EC2     (C2R-C2)*125000.
C1      Y3/Y1
H1      Y2/Y1
C2      Y5/Y4
SIGL1   (EW1+Y6)/KL1+SIGL10
DELV    3.9413*(EW2+Y7)/KL2
B1      1.33*EXP(.481,SIGL1)
B2      B20*EXP(DELV,10.)
T1      (H1+32.1-6.*C1)/(1.-.454*C1)
H2      T2*(1.-.454*C2)-32.1+6.*C2
Q2      UA2*(T1-T2)
HO2     1066.1+.4*T2
HVAP    1098.-.6*T1
HO1     1068.73+.386*T1
NUM     Q2-HL3+B1*(H1-H2-DHDC*(C1-C2))
DEN     DHDC*C2+HO2-H2
O2      NUM/DEN
O1      (Q2+HL2)/HVAP
FDERC2  100.*(B1*(C2-C1)-O2*C2)/(.0008*Y4)
SIGSI   (EC2+Y8+TDC2*FDERC2)/KC2+SIGSI0
SI      0.68*SDENS*EXP(.455,SIGSI)
TSI     (SI*(HSI+32.)+T1*UA1)/(UA1+SI)
Q1      UA1*(TSI-T1)
B1NOR   B10/1.33
SIGL10  EXP(2.079,B1NOR)
Y1      INT(F-B1-O1,W1R)
Y2      INT(F*HF+Q1-B1*H1-O1*HO1,Y20)
Y3      INT(F*CF-B1*C1,Y30)
Y4      INT(B1-B2-O2,W2R)
Y5      INT(B1*C1-B2*C2,Y50)
Y6      INT(EW1/TL1,0.0)
Y7      INT(EW2/TL2,0.0)
Y8      INT(EC2/TC2,0.0)
TIME    T-4.0
        FIN(T,184.)
        HDR(T,C1,C2,B1,B2,SI)
        HDR
        OUT(TIME,C1,C2,B1,B2,SI)
        END
END
```

APPENDIX 12

CALCULATION OF FILM COEFFICIENTS

In order to estimate the time constants pertaining to the steam cavity of the calandria and the calandria walls, values for the steam side and the solution side film coefficents are required. As mentioned in Chapter II the solution side film coefficient is the most difficult to obtain. Therefore an emperical correlation will be used to find the steam side film coefficient only. The solution side film coefficient will be obtained using the experimental average over-all film coefficient and the empirically calculated steam side film coefficient.

Steam Side of the First Effect Calandria

A reasonably accurate* theoretical equation for estimating the film coefficient for vapors condensing in laminar flow on vertical tubes is

$$h = 0.943 \left(\frac{K^3 \rho^2 g \lambda}{L\ y\ \Delta t}\right)^{1/4} \qquad (12\text{-}1)$$

h = film coefficient

k = thermal conductivity of condensate

ρ = density of condensate

g = acceleration of gravity

* McAdams, W.H., "Heat Transmission", McGraw-Hill Co., New York (1954)

λ = latent heat of vaporization

L = Length of tube

y = viscosity of condensate

t = temperature potential

The approximate values for these parameters are

k = .394 btu/hr. ^{o}F ft^{2}

ρ = 60 lbs/ft^{3}

g = 32 $(3600)^{2}$ ft./hr.^{2}

τ = 970 btu/lb.

L = 1.5 ft.

y = .864 lb./ft.hr.

t = 10.^{o}F

Substituting these values into equation (12-1) the condensing steam film coefficient is found to be

$$hs_1 = 1500 \text{ btu}/^{o}\text{F ft}^2\text{hr.}$$

therefore,

$$hs_1 = 25.3 \text{ btu}/^{o}\text{F ft}^2\text{min.}$$

or

$$hs_1A_1 = 235 \text{ btu}/^{o}\text{F min.}$$

<u>Solution side of the First Effect Calandria</u>

As mentioned in the main body of the thesis, determining heat transfer coefficients for boiling liquids in tubes is extremely difficult. Therefore, a value for the solution-side film coefficient will be obtained using experiment data.

From experimental results

$$U_1A_1(\text{ave}) = 58.7$$

and

$$\frac{1}{U_1A_1} = \frac{1}{hs_1A_1} + \frac{1}{h_1A_1}$$

therefore

$$h_1A_1 = \frac{(58.7)(235.)}{176.3}$$

$$= 78.2 \text{ btu}/^{\circ}\text{F min.}$$

APPENDIX 13

FLOW CONTROL, FIRST PRODUCT EFFECT

In Appendix 4 it was shown that the calibration curve for the first effect product flow (B) can be expressed by

$$B_1 = 1.33 \left(\frac{CR}{10}\right)^{.48}$$

where CR is the chart reading and is equal to Fb the flow transmitter output in percent. Therefore,

$$B_1 = 1.33 \left(\frac{Fb}{10}\right)^{.48}$$

and

$$Fb_1 = 10. \left(\frac{B_1}{1.33}\right)^{2.1}$$

In linear form the relationship between transmitter output and flow is

$$Fb_1 = Kft\ B_1 + \text{CONSTANT}$$

WHERE

$$Kft = \frac{Fb_1}{B_1} = \frac{(10)\ (2.1)}{(1.33)} \left(\frac{B_1}{1.33}\right)^{1.1}$$

Substituting the approximate average value of B_1 = 2.0 lbs.mmin. yields

$$Kft = 29.7\ \%/\text{lbs/min.}$$

Therefore

$$Fb_1 = 29.7\ B_1 + \text{CONSTANT} \qquad (13\text{-}1)$$

Although the value of the constant in the above equation can be obtained it is not required for the analysis in Chapter IV and therefore need not be evaluated.

As was the case for the second effect product flow (Chapter IV), the relationship between valve position and flow rate for the first effect is

$$B_1 = \overline{B}_1\ 10^{.0158\Delta v}$$

where

$\overline{B}_1$ = steady state flow rate

Δv = change in valve position (%) from this steady state

Assuming a one-to-one relationship between valve position and controller output

$$B_1 = \overline{B}_1\ 10^{.0158\Delta Cb_1}$$

where

ΔCb_1 = change in controller output from steady state

The linearized version of this equation is

$$B_1 = Kv_1 Cb_1 + \text{CONSTANT}$$

where

$$Kv_1 = \frac{\partial}{\partial Cb_1}(B_1)$$

$$Kv_1 = \bar{B}_1 (2.3)(.0158)$$

Assuming $\bar{B}_1$ = 2. lbs./min. yields

$$Kv_1 = .073$$

therefore,

$$B_1 = .073\ Cb_1 + \text{CONSTANT} \qquad (13\text{-}2)$$

As with equation (13-1) the constant in equation (13-2) need not be evaluated.

APPENDIX 14

EVAPORATOR DESIGN CALCULATIONS

Basis:

- assume feed rate = 100 lbs./hr.
- concentrate solution from 5% to 15%
- assume solution properties are approximately equal to those of water
- assume pressure in first effect = 18" Hg.
- assume pressure in second effect = 5" Hg.

Calculations:

Heat and Material Balances

First effect latent heat of vaporization ΔH = 986 btu/lbs.

Second effect latent heat of vaporization ΔH = 1018 btu/lbs.

Let X = evaporation rate, first effect, lbs./hr.

Y = evaporation rate, second effect, lbs./hr.

Heat removed for first effect = q_1 = 986X btu/hr.

Assume a 10% heat loss

therefore heat removed from second effect $q_2 = (.9)(986)X$

But $q_2 = 1018Y$

therefore

$$Y = \frac{(.9)(986)X}{1018}$$

by an overall solute balance

$$.15(100 - x - y) = (.05)(100)$$

Solving

$$X = 35.6 \text{ lbs./hr.}$$

$$Y = 31.1 \text{ lbs./hr.}$$

<u>First Effect</u>

- assume steam temperature = 215°F

$$\text{product composition} = \frac{(.05)(100.)}{(100. - 35.6)} = .0775$$

- heat transferred = (35.6)(986) = 35,000 btu/hr.
- assume U = 250 btu/lb.ft^{2}hr.(24)

Therefore

$$A = \frac{35{,}000}{(250)(30)} = 4 \text{ ft}^2$$

- for flexibility double the area to

$$A = 8 \text{ ft}^2$$

- use 3/4-inch 16 gauge stainless steel tubing 18 inches long. (average surface area = .17 ft^2/ft)

$$\text{no. of tubes} = \frac{8}{(1.5)\ (.17)} = 31.4 = 32 \text{ tubes}$$

diameter of the calandria downcomer equals 100% of the total x-sectional area of the heating tubes.

$$A = (32)(.00210) = 0.0672 \text{ ft}^2$$

$$D = \sqrt{\frac{4(.0672)}{\pi}} = .292 \text{ ft.} = 3\text{-}1/2 \text{ inches}$$

Second Effect

heat transferred = .9(35000) = 31,500 btu/lb.

- assume second effect temperature = 155°F

- temperature drop available = 185 - 155 = 30°F

Therefore,

$$UA = \frac{31,500}{30} = 1050 \text{ btu/hr.ft.}^2$$

- use 3 tubes 1-inch, 16 gauge, 6' long

  Surface area = .23 ft^2/ft

Therefore,

$$A = (.23)(3)(6) = 4.14 \text{ ft}^2$$

Therefore,

$$U = \frac{1050}{4.14} = 250 \text{ btu/hr.}^\circ\text{F ft}^2$$

This heat transfer coefficient is well within what can be expected for forced circulation evaporators* and therefore it is assumed that the design is okay.

---

* McAdams, W.H., "Heat Transmission", McGraw-Hill Co., New York (1954).